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THE PREPARATION AND SIGNIFICANCE OF FREE-AIR PRESSURE MAPS FOR THE CENTRAL AND EASTERN UNITED STATES.[1]

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[Author's abstract.]

[Weather Bureau, Washington, D. C., Oct. 15, 1922.]

Note: There has been issued recently under the above title Monthly Weather Review Supplement No. 21. It has been the practice to present in the Monthly Weather Review rather full abstracts of the material contained in the Supplements. This step is made in the interest of printing economy, for it is the hope that the general reader may be satisfied in this way without necessitating a large edition and without entailing waste through indiscriminate distribution of the Supplements. Therefore, those who find this subject one of special interest, and who desire to procure the complete discussion, may do so by applying to the Superintendent of Documents, Government Printing Office, Washington, D. C., who carries a limited supply in stock. The publication contains 77 pages, 31 figures, and 22 lithograph charts. The price is 25 cents.—Editor.

It is the purpose of this abstract to present concisely that material which has not been used in previous publications dealing with this subject. The material is largely excerpted from the extended publication mentioned above. Many tables, numerous figures and charts have not been reproduced. It is hoped, nevertheless, to illumine the salient features of the discussion, allowing the reader who so desires to seek the details in Supplement 21.

Those who have followed previous papers concerned with this research,[2] are aware of the principal difficulty confronted in the attempt to reduce barometric pressure from the elevation of the barometer to some arbitrary level. It is the difficulty of knowing accurately the mean temperature of the intervening column of air. If the reduction is to be upward, the air column is real; if it is to be downward, as at present in reducing to sea level, there is no actual air column, and, in this latter case, the problem is to find a temperature value which will yield smooth isobars. This paper is concerned with reduction upward, hence, with the determination of actual air temperatures.

There is scarcely a meteorological element that is more irregularly variable with change of altitude than temperature. The value of θ that would be ideal may be defined as a mean determined by integrating the current vertical temperature curve throughout the length of the air column under consideration. But this is manifestly impracticable. The equipment necessary for the observation of free-air temperatures can not be provided for the individual stations; and, if it could, the time required for the reduction of observations would render the plan ineffectual for the forecasting of weather. *The presen problem, therefore, becomes that of finding some clue, or index, observable at the surface, that will lead to a close approximation of the mean temperature of the air column.* When one considers the almost infinite variety of surface and free-air conditions that bear directly upon the temperature of the air column, the search seems, at the outset, rather unpromising; but the way is opened through the use of the surface-wind direction as a basis of classification.

The attempt to draw free-air pressure charts is not new. It has been attempted in one form or another and for various purposes by Teisserenc de Bort,[3] Köppen,[4] Bigelow,[5] Sandström,[6] Dietsch,[7] and Fujiwhara.[8] As long ago as 1882, Professor Abbe[9] said: "In fact, for all cases, the only natural method of reduction would seem to consist in an attempt to reduce upward through the actually existing atmosphere (whose temperature and moisture can be observed) to a uniform altitude."

WIND DIRECTION AS AN INDEX TO TEMPERATURES IN THE FREE AIR.

The need for an index.—In reducing to upper levels three elements are accurately known—(1) the vertical distance between the station and the reduction level, (2) the surface pressure, and (3) the surface temperature. There are two elements to be determined, (1) the mean temperature of the air column, and (2) the mean vapor pressure of the air column. The mean temperature affords the greater problem, for the water vapor effect is less influential. If the mean temperature can not be observed, it is imperative that some index, ***observable at the surface***, be employed. What shall this index be?

The qualifications of an index.—There are two qualifications to which such an index must conform: (1) It must have a direct physical relation to the temperature in the free air, and (2) it must be one of the weather

[1] A thesis presented to the Faculty of Graduate Studies, George Washington University, in part satisfaction of the requirements for the degree of Doctor of Philosophy, May 29, 1922.

[2] Meisinger, C. LeRoy: Preliminary steps in the making of free-air pressure and wind charts. Mo. Weather Rev., May, 1920, 48: 251–263; Progress in making free-air pressure and wind charts. *loc. cit.*, April, 1921, 49: 238–239; The Toronto symposium on pressure reductions. *loc. cit.* December, 1921, 49: 655–657.

[3] Étude sur la circulation génèral de l'atmosphére. *Annales du Bureau Central Météorologique de France*, 1885, Part IV, Météorologie général, second partie, pp. 35–44.

[4] Über die Gestalt der Isobaren in ihrer Abhängigkeit von Seehöhe und Temperatur-Verteilung. *Meteorologische Zeitschrift*, December, 1888, pp. 470–481.

[5] Report on the barometry of the United States, Canada, and the West Indies. *Report of the Chief of the Weather Bureau, 1900–1901*, Vol. II.

[6] On the construction of isobaric charts for high levels in the earth's atmosphere and their dynamic significance. *Transactions of the American Philosophical Society*, N. S., Vol. XXI, Part I, pp. 31–96.

[7] Untersuchungen über die Änderungen des Windes mit der Höhe in Zyklonen. *Veröffentlichungen des Geophysikalischen Instituts der Universität Leipzig*, Band II, Heft 5, 1918, pp. 197–234. Abstract in Mo. Weather Rev., July, 1920, p. 402.

[8] Pressure maps at 3 kilometers in Japan. Mo. Weather Rev., October, 1921, pp. 571–572.

[9] Appendix 61, *Report of the Chief Signal Officer*, 1882, Part 1, p. 826.

elements regularly observed at stations. The first of these qualifications is *scientifically* pertinent; the second is *practical*. It is often inadvisable to infuse too much of the purely practical into the preliminary research relative to such a problem as this; but in this case it seems evident that the factors of simplicity and practicability are inseparable from the scientific solution of the problem. For that reason it is desirable to impose this qualification upon the element selected.

Comparison of wind direction and atmospheric pressure as temperature controls in the lowest levels.—A careful consideration of the various elements observed regularly at meteorological stations will invariably eliminate all but one (excluding temperature and pressure, which are essential to the formula as stated above), and that one is *wind direction*. Surface pressure and temperature do, however, call for a word in this connection. Leaving the question of the cause of irregular barometric fluctuations, i. e., the cyclones and anticyclones of extratropical latitudes out of consideration, it is sufficient to say that temperature changes in the lowest levels of the atmosphere (only the lowest 2 kilometers will be considered here) are the result of the importation of warmer or cooler air. Such importation is the result of the blowing of the wind, and the blowing of the wind is the result of a pressure gradient, however established.

Many important discussions have centered about the cause of temperature changes in the free air, some meteorologists adhering to the belief that such changes are essentially dynamic in character,[10] and others that the changes result through the importation of air of different temperature.[11] But these discussions concern themselves with conditions at higher levels than are of interest here. It is generally agreed, it seems, that in the United States the temperature, owing to the continental character of the weather controls, at least below 3 kilometers, is more strongly related to the cource of the air (hence to wind direction) than to such effects as dynamic and radiational heating and cooling.

In 1919, correlation coefficients were worked up by W. S. Cloud, at that time assistant in the Aerological Division of the Weather Bureau, showing the relation between temperature, pressure, and the south component of the wind at the surface and at 3 kilometers, based upon approximately 200 observations. These gave values opposite in sign to those determined in Europe, and led Mr. Gregg to conclude that the factor of continentality with the attendant marked effects of wind direction was the cause of the obliteration of such dynamic effects as were pointed out by W. H. Dines, in England. Mr. Gregg states, in conclusion: "These figures [Cloud's correlation coefficients] confirm the conclusions already given, viz, that in the United States, particularly in the interior portions, wind direction exerts a greater influence on the air temperature than does the sea-level pressure." One may attribute wind direction to pressure distribution, but, in such event, the relation is, at best, only indirect between pressure and temperature, whereas between wind direction and temperature it is direct. This disposes of the measured element of surface barometric pressure as an index to upper temperatures.

Wind direction and temperature at the surface in relation to free-air temperatures.—Similarly, there is a good correlation in the United States, between surface temperature and wind direction. This holds at least as high as 3 kilometers. While, in considering seasonal or monthly normals, there appears to be a certain relation between temperature at the surface and at some free-air level, it is obvious that such a relation can not be expected to hold uniformly under day-to-day conditions. The vertical distribution of temperature is not constant, nor even regularly variable, but one which varies with type of weather, time of day, topography, etc. It is apparent, then, that if the relation between surface temperature and free-air temperature were used, it would have to be classified according to some other condition more representative of the type of weather. Wind direction would offer such a classification for reasons given above. Thus, it seems that wind direction stands as the logical element by which temperatures in the free air in the United States may be judged most readily; both surface pressure and temperature are but indirectly related to free-air temperature, while wind direction at the surface—the consequence of both these elements—is directly related.

General pressure distribution as an index.—It has been suggested that the position of the station with reference to the distribution of pressure should be the criterion for the estimation of temperatures aloft. It is believed, however, that this criterion fails with respect to the qualification of practicality. An observer *must* be able, without knowledge of widespread conditions, to apply whatever criterion is adopted Obviously, it is not until all the observations are collected upon the synoptic chart that one can determine the station's location with respect to the quadrant of the cyclone or anticyclone. Hence, this suggestion is, for current reductions, entirely impractical. If it were possible, as it is in statistical summaries, there is the additional drawback of being unable to assign the station definitely to a proper barometric situation.[12] Wind direction, however, being a direct result of the barometric situation, affords a satisfactory and simple expedient, and such classification is, in the last analysis, classification by pressure distribution.

The time element in wind direction.—One point has been raised in discussion that is worthy of careful consideration. Suppose that at a certain observation the temperature is $-15°$ C. and the wind south, of moderate velocity, but that it has changed to south only within the last hour. The observer using his observations as the fundamental data computes the probable mean temperature of the air column upon the basis of a south wind at the surface. Suppose, moreover, that the wind blows steadily from the south for 24 hours and in that time the surface temperature has risen to 0° C. under its influence. The mean temperature of the air column will be quite different in the two cases, as is the surface temperature; but, since the south wind was blowing at both observations, the observer will consider that the difference between the mean temperature of the air column and the surface temperature is the same at these times. Is such a device justified? This is a question of genuine importance for an answer to which one must look to the testimony of observations. The only answer that the writer can give at this time is based upon some statistical data gathered from the aerological stations at Mount Weather, Va., Drexel, Nebr., and Elllendale, N. Dak., and published in connection with preliminary considerations of this question of reduction upward.[13]

[10] Dines, W. H.: The characteristics of the free atmosphere. *Geophysical Memoires, No. 13*, Brit. Meteorological Off., 1919. Abstract MO. WEATHER REV., September, 1919, pp. 644–647, by W. R. Gregg.

[11] Gregg, W. R.: Vertical temperature distribution in the lowest 5 kilometers of cyclones and anticyclones. MO. WEATHER REV., September, 1919, pp. 647–649.

Douglas, C. K. M.: Temperature variations in the lowest 4 kilometers. *Quarterly Journal of the Royal Meteorological Society*, January, 1921, pp. 23–46.

[12] Except in the case of special investigations, such as the study of the dynamics of cyclones and anticyclones, this classification has been abandoned by the United States Weather Bureau in favor of classification by surface wind direction.

[13] Meisinger, C. LeRoy: Preliminary steps in the making of free-air pressure and wind charts. MO. WEATHER REV., May, 1920, pp. 255–267.

If there is a marked difference between the air column temperature when the wind has just set in and after it has been blowing for a considerable time, the probable variation or standard deviation of the individual cases from the mean should be large. In other words, if the probable variation is small, the individual observations must agree closely with the mean, and the time interval between onset and observation must be of slight importance. It was found that, taking the observations as a whole, at the three stations mentioned, the probable variation of the mean temperature of the air column from the mean in reducing to 1 kilometer above sea level (roughly, an air column of 700 meters) is only 1.3° C.; to 2 kilometers it is only 1.8° C., being slightly greater at inland than at coastal stations. In terms of pressure at ordinary conditions these variations are of the order of 0.5 mb. and 1.2 mb. at the two levels, respectively. It is believed that errors of this order of magnitude would not be serious, especially if they are distributed over considerable areas rather than localized. This is not to say that the consideration of the time factor would not reduce the probable variation, but it seems that the labor and tedium of this further classification would hardly be justified by the degree of increased accuracy.

The turning of wind with altitude.—The argument may be advanced that a certain wind direction at the surface does not necessarily indicate the turning of the upper wind and that, using the argument that importation is the chief factor in determining temperatures below 3 kilometers, an upper temperature may be quite different at two observations when the surface temperature and wind direction are the same; but the same argument advanced above will hold here. If such cases do occur (and they undoubtedly do), they are not frequent enough to exercise appreciable effects upon the reduced pressure.

But there is another way to approach the problem, and that is to study the results of aerological observations which have lately been summarized for the eastern and central United States by the Weather Bureau Aerological Division.[14]

We know that, as greater and greater elevations are attained by kites, pilot balloons, and other means, there is frequently and usually a turning of the wind, sometimes to the right and sometimes to the left. It is not of much importance whether this turning is much or little, *so long as it is the same under similar surface conditions.*

It follows, therefore, that if the turning is not the same under all conditions the deviation from surface direction should be small, if surface direction is to be a reliable index. In other words, surface wind direction may be regarded as a satisfactory guide to upper temperatures (1) if turning with altitude is constant, or nearly so, or (2) if deviation from surface direction is small. Mr. Gregg has arranged tables extremely convenient for this test.[15] In Table 10c is given the average deviation in degrees of the free-air winds from surface direction at different elevations above the several kite stations. In Table 15c is given the average percentage frequency of clockwise and counterclockwise turning for the same elevation and the same stations. The curves in the accompanying figure 1 are carried to the 3-kilometer level in order that the proper trend at the 2-kilometer level may be shown.

[14] Aerological Survey of the United States. MO. WEATHER REV. SUPPLEMENT No. 20.
[15] *Ibid.*, pp. 56 and 68.

It will be seen that the average elevation of the six stations is 250 meters and that the elevations are given above sea level. For each wind direction at the surface (8 points) there are three curves—summer, winter, and annual deviation. The small numbers just below the surface level indicate the wind direction in degrees, measuring clockwise from north, while the wind directions indicated near the 3-kilometer level are for 16 compass points. Above each of the eight points of the surface wind are shown frequency polygons of the average clockwise and counterclockwise turning expressed as percentages of the total observations. The darker shading indicates clockwise and the lighter shading counterclockwise turning, while the unshaded portion indicates no turning at all. The deviation curves for the southeast wind, owing to their marked and rapid turning toward the west, are to be found in the lower tier at the left.

It will now be instructive to examine these curves with special reference to the consideration set forth above. In the first place, what of the constancy of turning? For this we may study the eight polygons. Taking a broad survey of the eight graphs, we find that there is a marked seasonal difference, as well as a difference between the several directions. The outstanding features of the polygons may be enumerated as follows:

(1) There is more frequent turning of winds from surface direction in all seasons at the 2-kilometer level than at the 1-kilometer level. This is a well-known fact, but a short table of the percentage of times there is *no* change is of interest, the annual average only being considered.

TABLE 1.—*Percentage frequency of no turning of wind with altitude (annual average).*

Elevation.	N.	NE.	E.	SE.	S.	SW.	W.	NW.
1 km.	53	44	33	22	35	38	44	53
2 km.	27	33	16	12	14	23	31	44

It is clear from this table that northerly winds are the deepest and most likely to persist up to the 2-kilometer level, while east, southeast, and south winds are most likely to turn below this level.

(2) At the 1-kilometer level clockwise turning occurs most frequently with southeast winds and least frequently with northwest winds, the transition from one to another being quite gradual.

(3) At the 1-kilometer level counterclockwise turning occurs most frequently with northwest and north winds, and least frequently with southeast and south winds, the frequency of clockwise turning being rather small.

(4) At the 2-kilometer level clockwise turning occurs most frequently with southeast winds and least frequently with northwest or north winds.

(5) At the 2-kilometer level counterclockwise turning occurs most frequently with north and northeast winds and least frequently with southeast winds, the frequency relative to clockwise turning being considerably greater, especially with northerly winds, than is the case at the 1-kilometer level.

(6) The first precept—that concerning the greatest constancy of turning—is fulfilled by southerly winds, especially southeast.

Let us now examine the portion of the diagram dealing with the average deviations from surface direction, bearing especially in mind the importance of the *amount* of the deviation and its relation to the constancy of turning

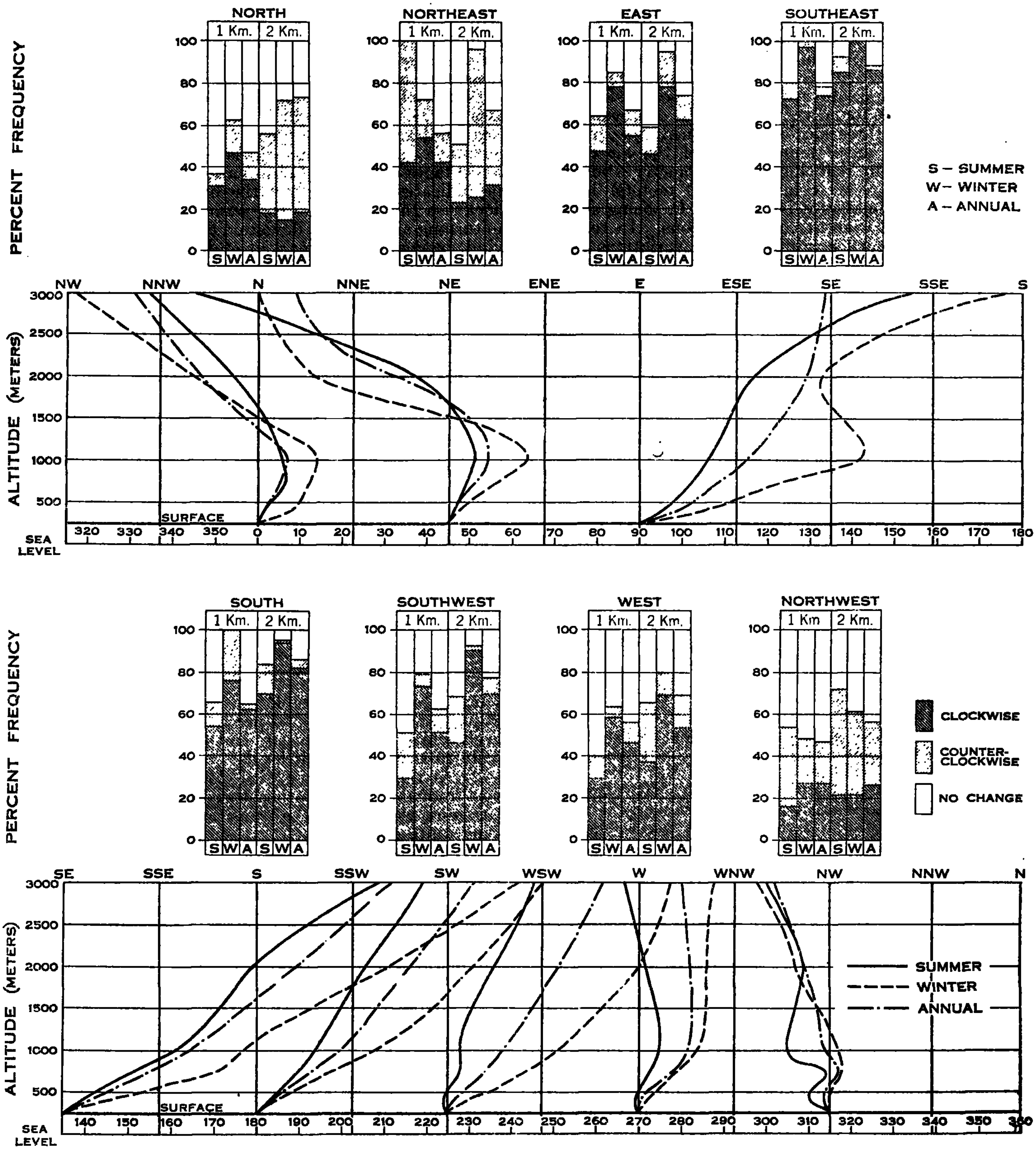


Fig. 1.—Summer, winter, and annual average turning of winds with altitude from the eight surface directions, and the percentage frequency of clockwise and counterclockwise turning.

discussed above. The following features appear worthy of consideration:

(1) At the 1-kilometer level all winds except northwest deviate clockwise. With northwest winds the winter deviation is clockwise also by a very small amount, but the summer and annual curves tend counterclockwise.

(2) At the 1-kilometer level the maximum deviation in the clockwise direction occurs with east and southeast winds. In winter this deviation amounts to more than 45°.

(3) At the 1-kilometer level the clockwise deviation is much less in summer than in winter; with northwest winds, mentioned in (1), the summer deviation is counterclockwise.

(4) At the 2-kilometer level all winds, excepting north, northeast, and northwest, deviate clockwise; in the three exceptions the deviations are decidedly counterwise.

(5) At the 2-kilometer level the maximum clockwise deviation occurs with southeast winds, where, in winter, it amounts to as much as 75°.

(6) At the 2-kilometer level the maximum counterclockwise deviation occurs with northeast winds, where, in winter, it amounts to about 30°.

(7) At the 2-kilometer level the clockwise deviation is more pronounced in winter than in summer. This is also true in the case of the three northerly winds mentioned in (4) with respect to counterclockwise deviation.

(8) The second precept—that concerned with the occurrence of the smallest average deviation—is fulfilled with the northwest wind.

It thus appears that the earlier contention that wind direction is a reliable index to upper temperatures is verified by these considerations. It was seen from the frequency polygons that the turning is most frequently the same aloft when the winds are southerly, but that the average deviation from surface direction is least when the winds are northerly. *The greatest average deviation occurs with greatest reliability of turning; the least deviation occurs with the least reliability of turning.*

The conclusion is, therefore, that the available statistical evidence is decidedly favorable to the use of surface wind direction in the capacity of an index to the thermal conditions aloft.

THE EVALUATION AND GEOGRAPHICAL DISTRIBUTION OF Δ.

The data.—The collection of data consisted in going over the individual kite flights and determining the mean temperature of the air column, finding its difference from the surface temperature, and classifying this difference by wind direction (eight points) and by months. The record sheets of the flights prepared in the Aerological Division of the Weather Bureau give the conditions of temperature, pressure, vapor pressure, etc., at frequent altitude stages, and the simultaneous surface conditions. In determining the mean temperature of the air column between the surface and a chosen level, say 1 kilometer above sea level, it was necessary to weight the mean temperatures of several layers intervening according to the depth of each layer. In this way, the mean temperature of the required air column was the weighted mean of several layers whose mean temperature could be very accurately determined. Inspection of the vertical curves of temperature indicates that, when carefully performed, this method of integration is sufficiently accurate.

Definition of Δ.—Experience has indicated that confusion may arise in the use of the rather prolix expression "difference between the mean temperature of the air column and the surface temperature," a phrase that has been used a great deal. A symbol for this quantity is desirable since it will be necessary to refer to it again and again. Consequently from the following relation,

$$t+\Delta=\theta,$$

in which t represents the surface temperature, θ the mean temperature of the air column, and Δ the difference between the two, it appears that Δ will fulfill this need satisfactorily.[16] It has been used throughout the paper.

The aerological stations.—The data were drawn from the seven kite stations of the Weather Bureau, two of which have since been discontinued. They comprise four stations in an approximately north-south line in the Middle West—Ellendale, N. Dak.; Drexel, Nebr.; Broken Arrow, Okla.; and Groesbeck, Tex.;—a station at Royal Center, Ind.; one at Leesburg, Ga.; and one at Mount Weather, Va. The last two stations are no longer in operation, the former having been replaced about the end of 1920 by one more satisfactorily located at Due West, S. C., and the latter discontinued in 1914, after seven years of active work. The preliminary studies were concerned only with Mount Weather, Ellendale, and Drexel, but the present paper has been based upon all flights occurring about 8 a. m., 75th meridian time, at all stations up to the beginning of 1921. The data at Due West have not been considered because this station has been established so recently that the means of the difference between the surface temperature and the mean temperature of the air column would not be very reliable. Moreover, Due West affords an interesting opportunity to test the accuracy of the computed pressure maps.

The total number of kite observations examined and tabulated is over 5,000 when all stations are considered. It is seen that even when this number is subdivided and apportioned to the several stations and further divided by classification into months and wind directions the numbers of observations upon which the means are based are large enough to justify a considerable degree of confidence. For some wind directions the number is larger than for others, but, fortunately, in such cases the number of observations is a fair index of the frequency of occurrence of such winds, and the low reliability of certain values is offset statistically by the paucity of occurrences.

The reduction levels.—Two free-air levels, 1 and 2 kilometers above sea level, respectively, were chosen. There are several reasons why these particular levels seemed most desirable, namely, (1) the largest amount of aerological data was available for these lower levels, since the number of kite flights that reached altitudes greater than 2 kilometers above sea level falls off rapidly; (2) it is at about these levels that the greatest amount of flying takes place, hence maps of pressure there would be of the greatest benefit to aviators; and (3) above 2 kilometers the

[16] A clear distinction should be made by the reader between the term Δt commonly used in aerology and the symbol Δ used in this paper. The former is a symbol used to denote the *rate of change of temperature with altitude*. It is called the vertical temperature gradient or lapse rate and usually is the amount of temperature change per altitude change of 100 meters. Its sign is *positive* when temperature *falls* with increase of altitude and *negative* in the case of *inversion*. The following quotation from the recommendation of the Subcommission on International Publications at Monaco, in 1909, gives the basis for this usage:

"La Sous-Commission recommande d'adopter, pour la définition du signe du gradient vertical de la température, le systeme ou le gradient sera positif lorsque la température diminue à mesure que la hauteur augmente, et que le gradient sera négatif dans la cas contraire." (*Sixième Reunion de la Commission Internationale pour l'aerostation scientifique à Monaco du 31 mars au 6 avril, 1909.* Strasbourg, 1910.)

On the other hand, the symbol Δ does not represent a lapse *rate*; it represents an actual *difference of temperature* between two points in a vertical in the atmosphere, one at the surface and the other in the free air at a level representative of the air column in question. Hence, when the temperature *falls* with altitude, the value of Δ is *negative*, and when temperature *rises* the sign is *positive*. Owing to this difference of sign, it is imperative that Δt and Δ be not confused.

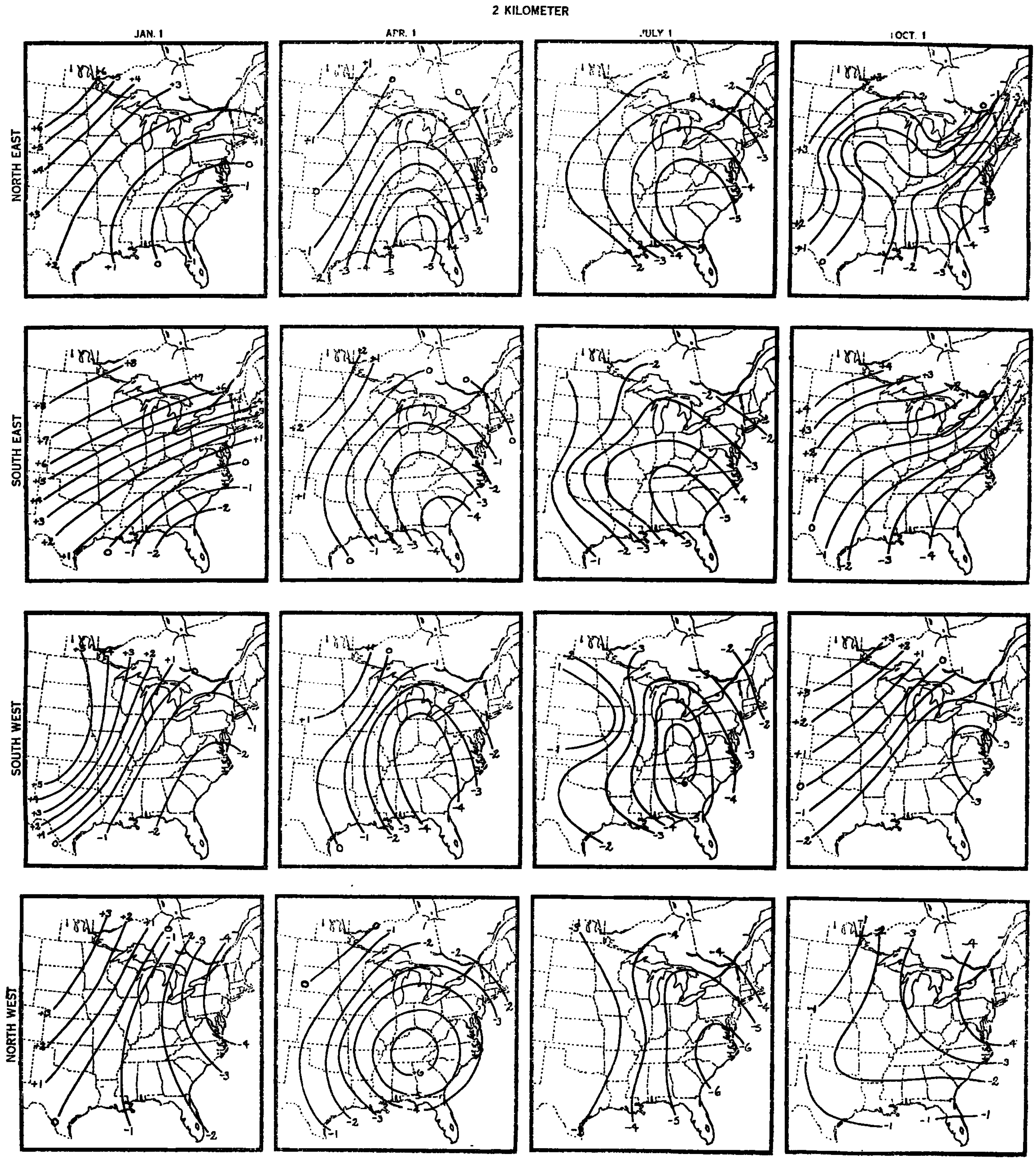


FIG. 2.—Specimen charts of the distribution of Δ at 2 kilometers.

tendency for isobars to lie prevailingly from west to east becomes apparent. The weaker pressure formations may not extend above that height, yet they may have a profound influence upon the surface weather.

Below 1 kilometer, the effect of surface-induced turbulence may, and does, have considerable influence in deflecting winds from the gradient direction and in preventing them from attaining gradient speed. Thus, the 1 and 2 kilometer levels seem acceptable as trial levels for pressure reductions.

The time of observation.—In selecting the flights from which the data were obtained, an attempt was made to take only those representative of conditions about 8 a. m., 75th meridian time. The average time of kite flights at various aerological stations is about 10 a. m., but flights occurring much later or much earlier than 8 a. m. were not included in this study. The purpose in using only those observations was to get temperature relations that would be applicable to the regular morning observations at Weather Bureau stations. Therefore, while it is undoubtedly true that the mean time of the observations contained herein is not precisely 8 a. m., it must lie within a few minutes of that time, and, for all practical purposes, the change in temperature owing to this time difference would be negligible.

Owing to the small number of flights occurring during the evening hours, no attempt has been made to prepare similar data for the 8 p. m. observation. Work must, however, be done along this line, possibly as the next step in this research.

Treatment of original data.—The data, after being compiled as indicated above, were modified so as to include the thermal effect of mean monthly vapor pressure and smoothed graphically by means of lines showing equal values of Δ on coordinates of surface wind direction and months. This was done for each level and for each of the kite stations. The smoothed values of Δ were then plotted on maps of the eastern United States and lines of equal value of Δ were drawn, thus showing the geographical distribution. Figure 2 shows some of these maps. From such charts it was possible to interpolate for intermediate reporting stations of the Weather Bureau.

The selection of stations.—An attempt was made to select about 30 regular Weather Bureau stations having good anemoscope exposures. It must be confessed that this was difficult. The location of wind vanes on high buildings in large cities where they are affected by eddies caused by surrounding buildings or architectural features not infrequently renders the recorded wind direction at variance with the direction at surrounding stations and the general flow indicated by the isobars. Again, certain anemoscope exposures are not comparable with those at surrounding stations because of topographic irregularities, valleys, slopes, etc., which deflect the vane from the direction the pressure gradient requires. Perhaps there have been included in this list some that are not the best from this viewpoint.

Another qualification, however, is that they shall be rather evenly spaced about the country within the limits deemed safe for interpolation. The following table gives a list of the 32 stations selected, their altitudes above sea level, and the length of the air column to the two reduction levels:

TABLE 2.—*The stations, their altitudes and distances from the two reduction levels (meters).*

Station.	Altitude above m. s. l.	Length of air column to—	
		1 km. above m. s. l.	2 km. above m. s. l.
Albany, N. Y.	30	970	1,970
New York, N. Y.	96	904	1,904
Washington, D. C.	34	966	1,966
Norfolk, Va.	28	972	1,972
Wilmington, N. C.	24	976	1,976
Columbia, S. C.	107	893	1,893
Jacksonville, Fla.	13	987	1,987
Atlanta, Ga.	358	642	1,642
Thomasville, Ga.	83	917	1,917
Pensacola, Fla.	17	983	1,983
Anniston, Ala.	226	774	1,774
Vicksburg, Miss.	75	925	1,925
New Orleans, La.	16	984	1,984
Houston, Tex.	42	958	1,958
Little Rock, Ark.	109	891	1,891
Memphis, Tenn.	121	879	1,879
Nashville, Tenn.	166	834	1,834
Lexington, Ky.	301	699	1,699
Indianapolis, Ind.	250	750	1,750
Columbus, Ohio.	250	750	1,750
Pittsburgh, Pa.	257	743	1,743
Buffalo, N. Y.	231	769	1,769
Port Huron, Mich.	194	806	1,806
Duluth, Minn.	345	655	1,655
Moorhead, Minn.	286	714	1,714
Madison, Wis.	297	703	1,703
Des Moines, Iowa.	262	738	1,738
St. Louis, Mo.	173	827	1,827
Yankton, S. Dak.	376	624	1,624
Concordia, Kans.	424	576	1,576
Oklahoma City, Okla.	370	630	1,030
Abilene, Tex.	530	470	1,470

Figure 3 shows the distribution of the interpolated reporting stations which were used as reduction points in the maps that follow.

TESTING THE METHOD.

The nature of the tests.—Before proceeding with the values of Δ deduced in the foregoing pages to the actual making of upper maps, it is desirable to subject the scheme to as many tests as possible. It is practically impossible at the present time to know the absolute synchronous pressure distribution at free-air levels; hence comparisons of pressures computed by this method with those actually existing are difficult. But three methods of approaching such tests suggest themselves, the first being direct while the second and third are indirect but dependent upon well-known and theoretically sound physical relations. These methods are:

(1) The comparison of computed pressures with those actually measured with kites. The Due West, S. C., station was inaugurated so recently that it was impossible to include in the data of this paper observations from that station. Such values of Δ as may be applied to Due West must be interpolated from the maps of the previous chapter and are in no way influenced by actual observations at that point. If, then, such interpolated values of Δ yield temperature arguments giving computed pressure in good agreement with those observed, the method may be regarded as satisfactory.

(2) Having made maps based upon observed free-air wind velocities and gradient wind relations, it is now possible to make comparison maps computed from surface data. If the two maps agree, confidence in both will be increased.

(3) On certain days when widespread pilot-balloon observations were made up to 2 kilometers it was possible to prepare computed maps for the 1 and 2 kilometer levels and, upon the basis of the gradient wind relations, to compare the observed direction and speed of the wind with the trend and spacing of the isobars.

Computations for Due West, S. C.—Considering the first plan, the procedure for comparing computed with observed pressure values as obtained by the meteorograph at Due West was as follows:

(1) The aerological records of 42 kite flights made at about 8 a. m. and reaching the 2-kilometer level were selected at random except that a general seasonal distribution was sought. These 42 flights were made between March 6, 1921, and January 11, 1922.

(2) The surface data at the beginning of the flights were the bases for the computations and consisted of wind direction, pressure, and temperature. These were tabulated, together with the observed pressures, for the 1 and 2 kilometer levels.

(3) Values of Δ interpolated from the maps were applied to the surface temperature and the pressure at the upper level computed by the hypsometric formula.

The average difference for the 1-kilometer level was −0.5 mb. and for the 2-kilometer level −1.4 mb. This average difference, it will be noted, is negative, indicating that the computed pressure is, on the average, too low. The following effects may account for such a tendency:

(1) Change of pressure at upper levels between the time of kite launching, or, more precisely, the epoch of the computation, 8 a. m., and the time of the arrival of the kite at upper levels. This may be the result of irregular variations of pressure due to the approach or recession of cyclonic areas, or the diurnal variation of pressure, or both. These effects were estimated at 0.2 mb. and 0.3 mb., respectively, for the 1 and 2 kilometer levels; and, being of the proper sign, when applied to the average differences above, decreased them to −0.3 mb. and −1.1 mb. for the two levels respectively.

(2) Change of pressure at upper levels during the interval mentioned in (1) resulting from the diurnal change of temperature in the low levels of the atmosphere. This effect was estimated at 0.1 mb. and 0.2 mb. for the two levels, respectively, and further decreased the outstanding difference to −0.2 mb. and −0.9 mb., respectively.

(3) The residual negative tendency is small enough to exert but little effect upon the whole map when it is considered that the isobars will be drawn for intervals of 2.5 mb., horizontal difference of pressure. Moreover, such tendencies will probably not be localized at certain stations but will, in general, be operative over considerable areas, with the result that the horizontal gradients of pressure will be but little affected. It is the gradient rather than the absolute pressure that is of chief concern.

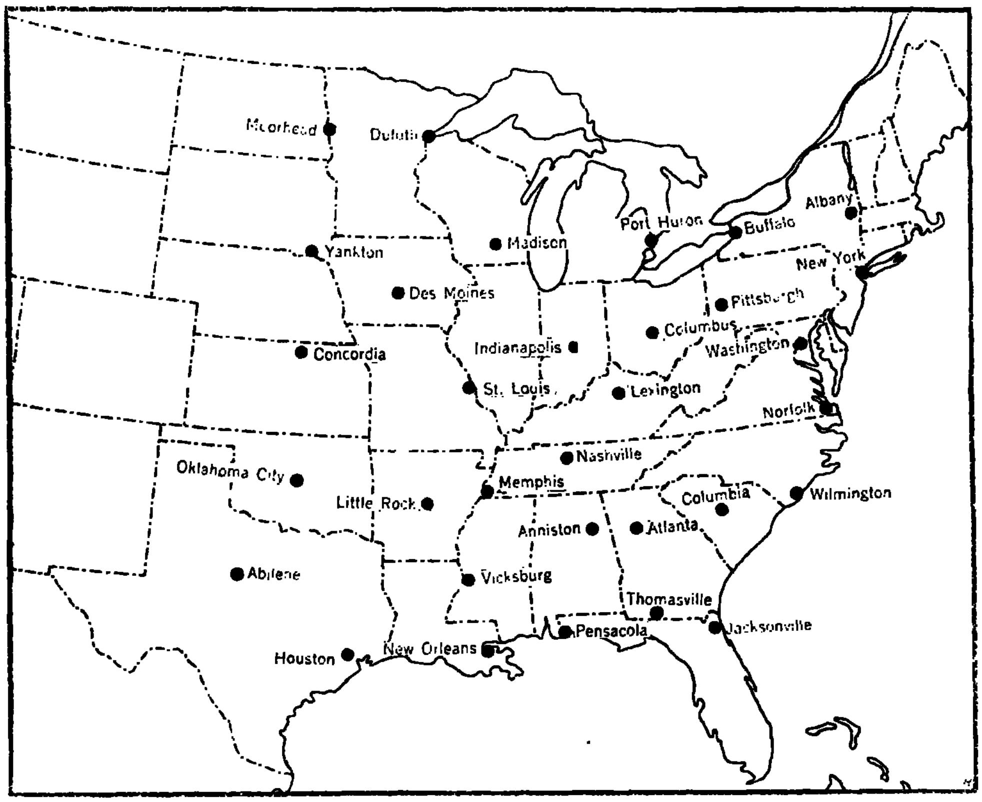


FIG. 3.—Reduction stations employed in the study.

Pressure maps from observed wind velocities.—From the gradient-wind equations it is possible to compute the velocity of the gradient; latitude, density, and radius of curvature of wind path are known. Conversely, if the gradient dp/dn is unknown, but the speed of the wind is observed by kite or pilot balloons, it is possible to solve the equations for the gradient. If this is done for a number of stations, the distance between isobars can be computed and the distribution of pressure at the upper level determined, the trend of the isobars being indicated by the observed wind directions. A few kite flights reaching the required levels enable one to assign actual values to the isobars, thus completing the map.

In 1920, as a matter of interest, this was done.[17] Figures 4, 5, and 6 show, respectively, the barometric situation at 8 a. m., March 27, 1920, at sea level, 1 kilometer,

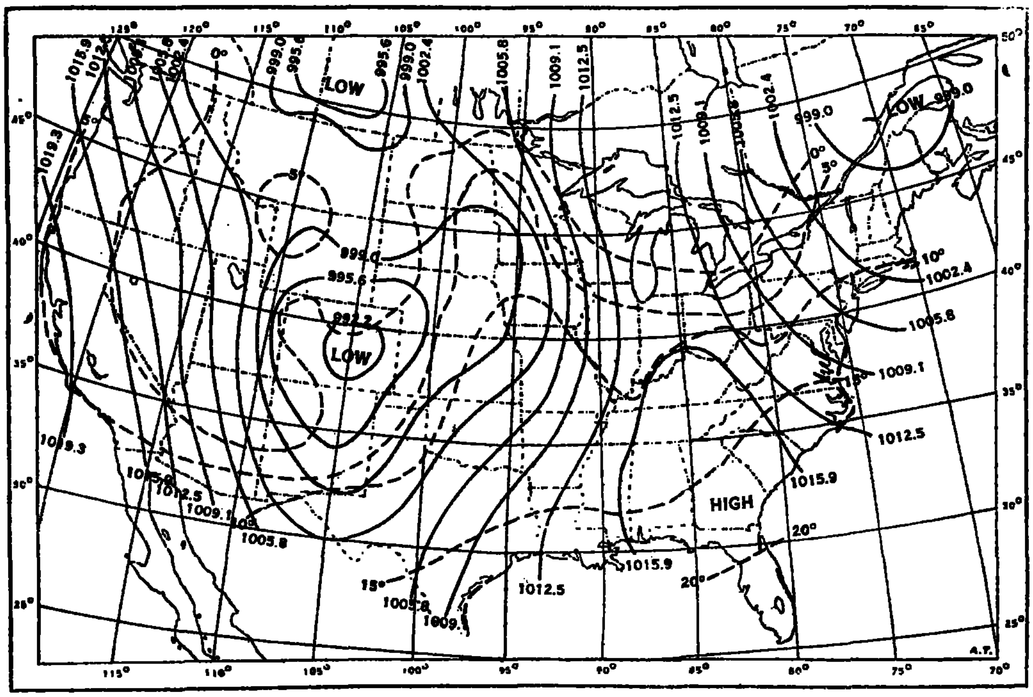


FIG. 4.—Sea-level weather map, March 27, 1920, 8 a. m., 75th meridian time. (Reprinted from MO. WEATHER REV., 1920, p. 700.)

and 2 kilometers above sea level. These maps are reprinted from that article. The wind arrows show the directions from which the trend of the isobars was determined. At that time it was impracticable to compute the pressure at the upper levels in any other way; with the completion of the tables of Δ, however, it is now possible to compute a map for the same date and time based only upon surface conditions. The similarity of the two sets of maps thus independently arrived at indicates not only that both are substantially correct but also that the Δ-method of computing pressures is reliable.

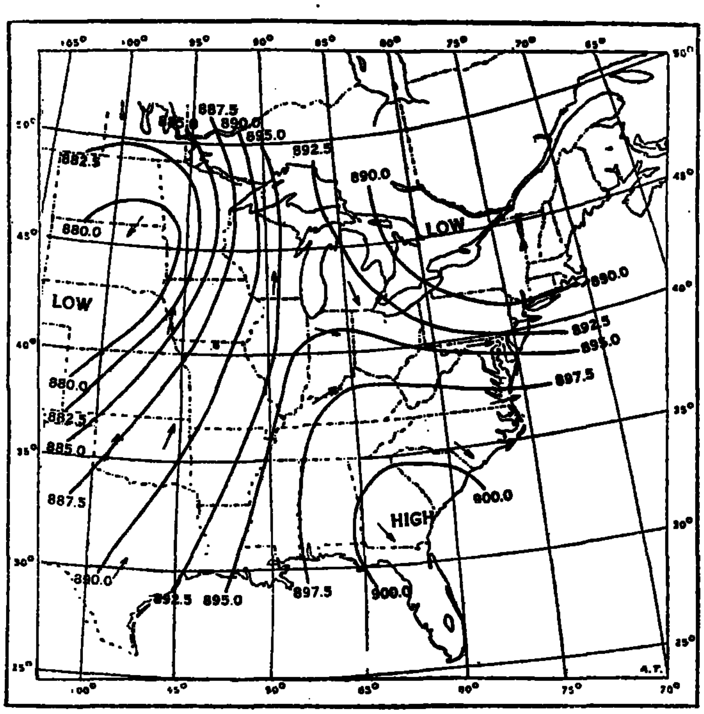


FIG. 5.—Pressure at 1 kilometer above sea level, in millibars, March 27, 1920, 8 a. m., 75th meridian time. (Reprinted from MO. WEATHER REV., 1920, p. 700.)

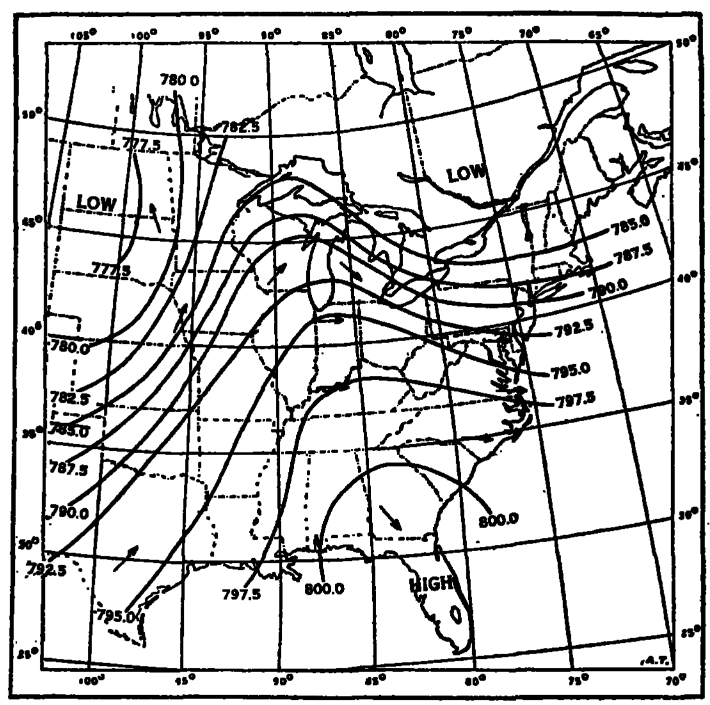


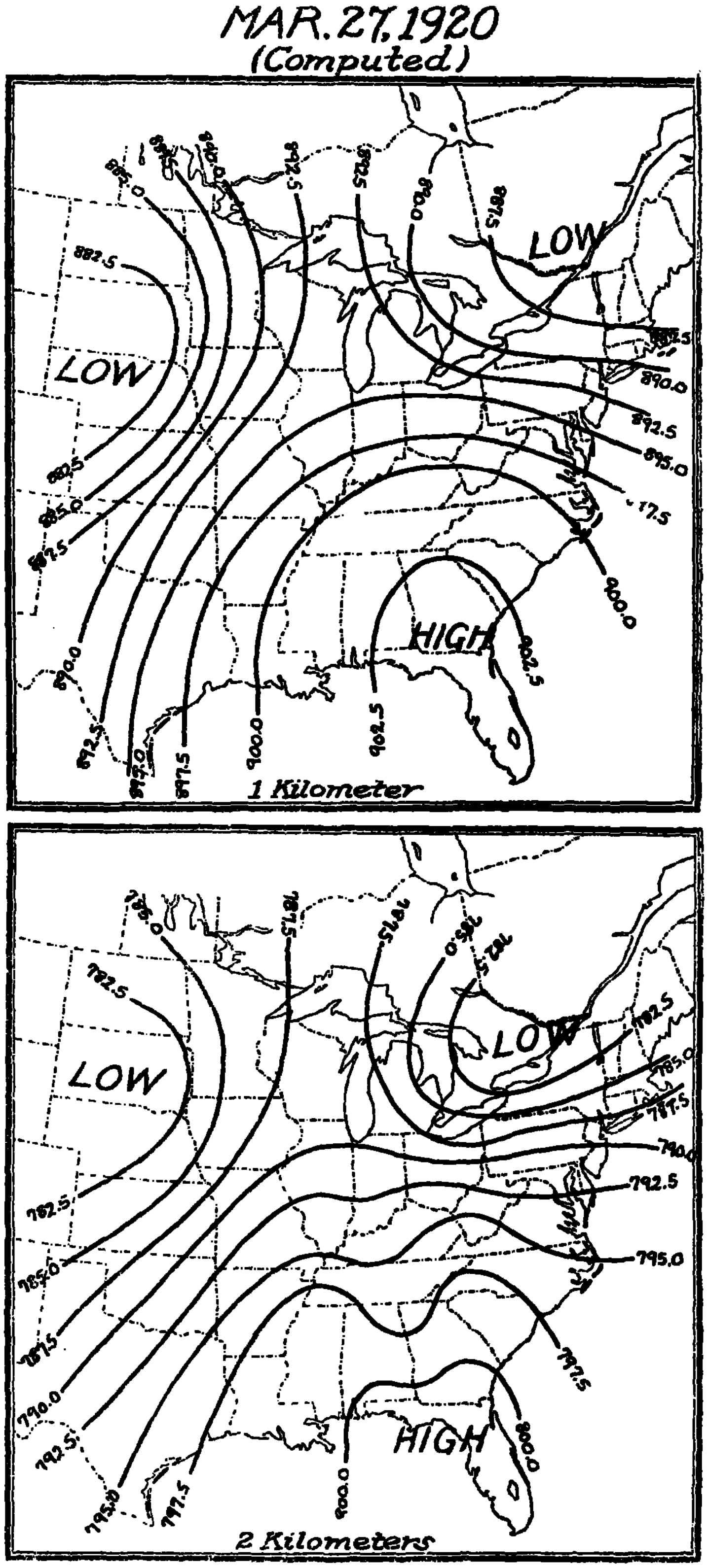
FIG. 6.—Pressure at 2 kilometers above sea level, in millibars, March 27, 1920, 8 a. m., 75th meridian time. (Reprinted from MO. WEATHER REV., 1920, p. 700.)

The reader is therefore invited to compare Figures 5 and 6 with figures 7 and 8. It is needless to say that the agreement is striking.

Computed maps and observed winds.—In line with the above idea is that of drawing free-air pressure maps by

[17] Meisinger, C. Le Roy: The making of upper-air pressure maps from observed wind velocities. MO. WEATHER REV., Dec., 1920, pp. 697-701.

computation alone, and then comparing them with free-air wind observations at as many stations as possible. This is substantially the same idea as that employed



FIGS. 7–8.—Pressure distribution at 1 and 2 kilometers above sea level, March 27, 1920, 8 a. m., 75th meridian time, computed from surface data.

above, except that no map is drawn from the observed wind velocities.

The Aerological Division, from an inspection of its records, supplied a list of dates when widespread pilot-balloon observations were made at the several stations of the Weather Bureau, the Signal Corps, and the Navy. Pressure maps, based entirely upon surface data, were computed. The observed winds were then compared with the maps. It must be remembered that the wind arrows were entered upon the maps *after* they were drawn, and were in no way influential in determining the distribution of the isobars. Figures 9 to 10 show the result.

Comparison maps at 1 and 2 kilometers.—In general, the maps (Figs. 9 and 10) speak for themselves, and, when studied with respect to the various considerations presented earlier in this section and in connection with the table of observed wind speeds at the two levels (Table 3), the agreement in nearly all cases is strikingly satisfactory. In fact, only one map (several additional dates were studied which are not presented graphically in this abstract), that of August 23, showed wind arrows that were not in good agreement with the isobars. Table 3, however, shows that, with very few exceptions, the wind speeds over the entire country were low; in fact, the air was generally stagnant. There were only two observations where the wind exceeded 10 meters per second, namely, at the 1-kilometer level at Broken Arrow, Okla., and at the 2-kilometer level at Lee Hall, Va. In the vicinity of these stations, however, the winds were light, and, since the pilot-balloon speed is really the result of only a momentary observation, it is altogether possible that the balloon was under the influence of local convection, which might give rise to a momentary lurch or turbulent gust.

Kite flights were made at the same time at Ellendale, Drexel, Broken Arrow, and Royal Center. At all places, the direction given pilot balloons and kites is in substantial agreement, and the same can be said of the speed, except at Royal Center, at the 1-kilometer level, where the pilot-balloon speed was 4 m. p. s. as opposed to 10 m. p. s. registered by the kite.

It should be noted that the horizontal temperature gradient between Duluth and Key West was only about 12° C., and the θ-gradient from which the free-air pressures were computed were only 6.7° C. at the 1-kilometer level and 8.6° C. at the 2-kilometer level, between Duluth and Jacksonville. This is in accord with the point which has often been made, that, under conditions of a week latitudinal temperature gradient at the surface, the upper winds may be expected to be light and variable; with a steep temperature gradient, the sea-level pressure formations change rapidly with altitude and the isobars tend to lie from west to east at relatively low elevations.

It is easily seen, therefore, from these maps, that when the pressure formations are relatively well defined, the agreement of observed winds with computed isobars is best; when the map is "flat" and the pressure formations vague and irregular, the agreement is not so dependable. This, however, does not militate against the accuracy of the computed isobars, for it is a well-known fact that light and variable winds always accompany such pressure formations when the horizontal temperature gradient is weak. These maps have their particular application to aviation, but, under conditions of light winds, the problem of aerial navigation is correspondingly simplified. On such stagnant summer days, the aviator is more concerned with the vertical component of the air than the horizontal. On August 28, 1921, there was probably not a single section east of the Mississippi and Ohio Rivers where the wind speeds were of sufficient magnitude to be a factor in the navigation of either lighter-than-air or heavier-

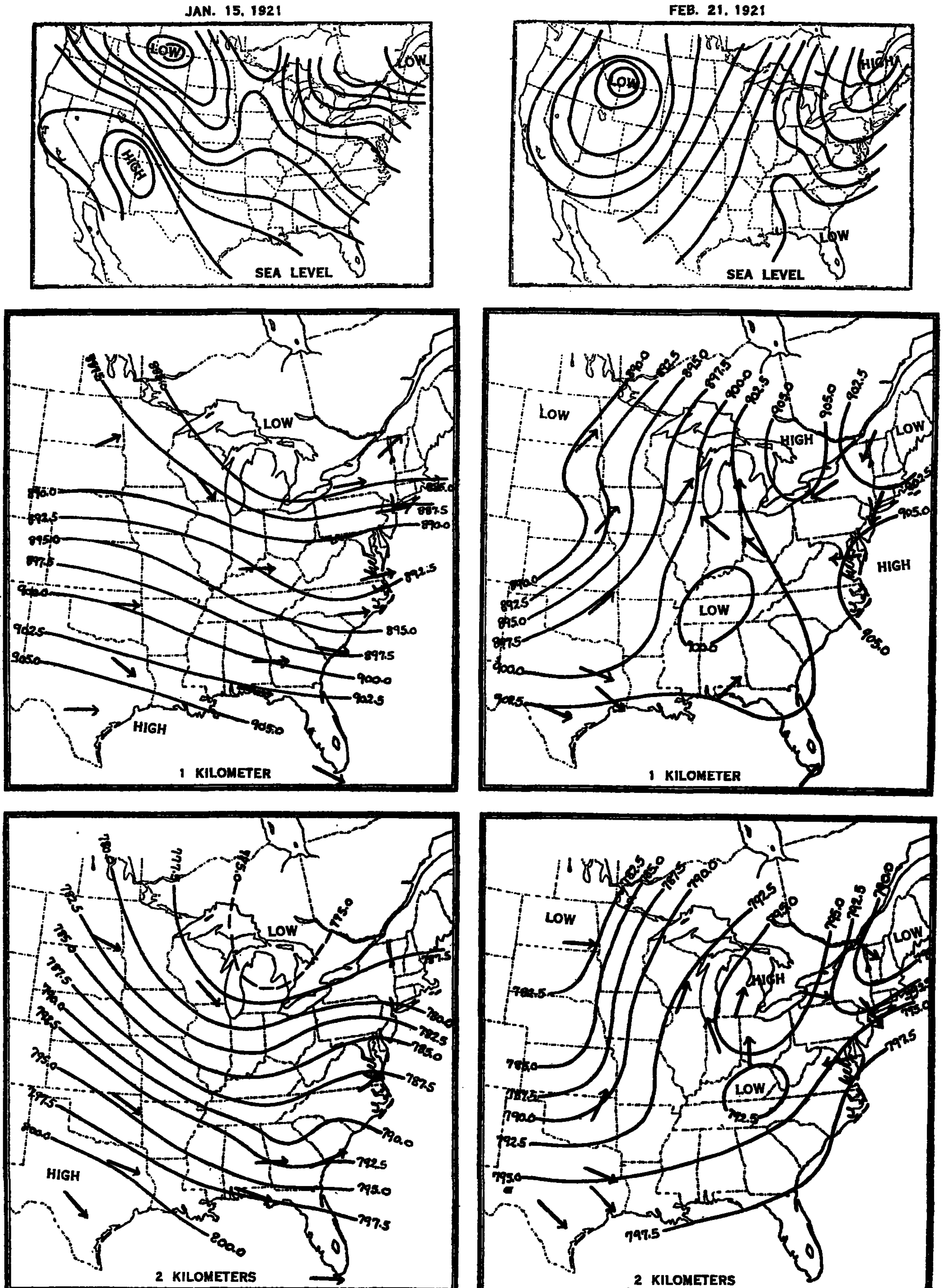


FIG. 9.—Pressure distribution at sea level and at 1 and 2 kilometers above sea level on January 15, 1921, and February 21, 1921, compared with winds observed at aerological stations.

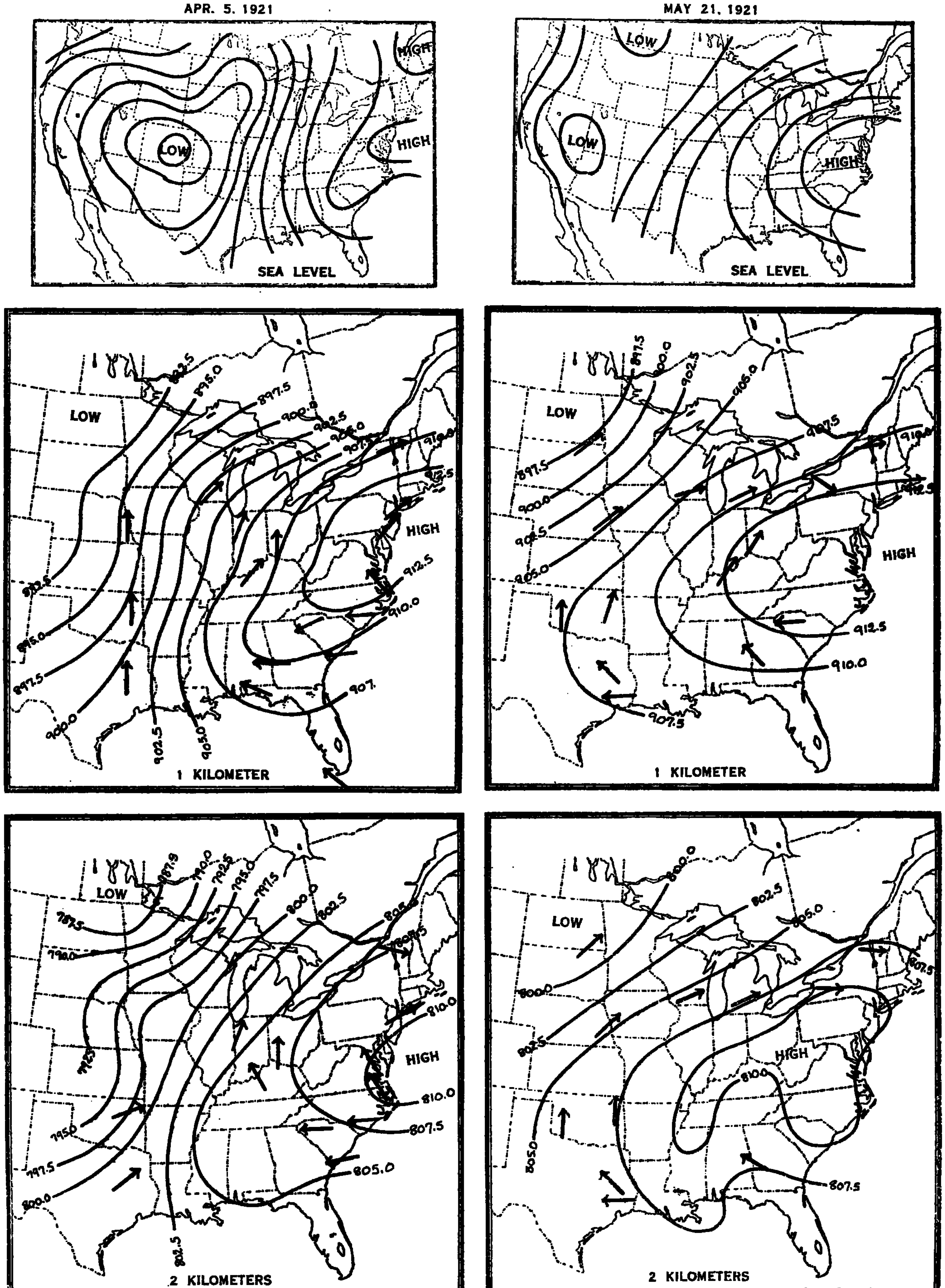


FIG. 10.—Pressure distribution at sea level and at 1 and 2 kilometers above sea level on April 5, 1921, and May 21, 1921, compared with winds observed at aerological stations.

than-air craft.[18] West of these regions, where the observed winds were stronger, the pressure formation was more definite and the agreement in direction better. Attention is called to the fact that the tongue of low pressure protruding from the Southwest into the Missouri Valley was more pronounced at the upper levels than at sea level, and its reality is confirmed strongly by the Ellendale, Drexel, and Broken Arrow observations.

TABLE 3.—*Velocities of observed winds at pilot balloon stations (m. p. s.).*

Station.	Km.	Jan. 15.	Feb. 21.	Apr. 5.	May 21.	July 8.	July 8.	Aug. 23.	Sept. 26.
Burlington, Vt.	1	9	7	9	13	5	3	......	......
	2	......	8	11	12	7	3	......	......
Ithaca, N. Y.	1	12	6	3	8	17	3	......	......
	2	......	4	......	8	21	5	......	......
Mitchell Field	1	12	9	11	......	......	......	3	11
	2	......	10	7	......	......	......	5	16
Lakehurst, N. J.	1	......	......	8	......	......	......	......	......
	2	......	......	2	......	......	......	......	......
Washington, D. C.	1	......	10	4	1	5	2	5	9
	2	......	7	5	2	10	2	7	12
Lee Hall, Va.	1	13	......	5	1	6	4	9	2
	2	......	......	10	1	10	1	13	......
Camp Bragg, N. C.	1	6	......	8	4	7	3	7	......
	2	......	......	8	......	5	2	7	......
Due West, S. C.	1	......	......	12	5	10	2	5	3
	2	......	......	8	......	2	3	4	2
Parris Island, S. C.	1	16	10	10	......	......	......	......	......
	2	20	......	6	......	......	......	......	......
Key West, Fla.	1	14	3	7	......	5	10	2	5
	2	29	......	1	......	5	8	4	4
Pensacola, Fla.	1	18	8	9	......	9	7	7	4
	2	25	......	......	......	5	......	9	3
Camp Benning, Ga.	1	17	......	12	8	5	......	8	4
	2	23	......	2	......	5	......	2	5
Camp Knox, Ky.	1	11	......	7	8	8	15	5	......
	2	......	......	7	4	11	10	5	......
McCook Field, Ohio.	1	......	8	5	5	......	10	1	5
	2	......	8	5	3	......	8	3	4
Royal Center, Ind.	1	......	4	12	3	7	9	[1] 4–10	8
	2	......	6	14	2	3	10	6	2
Lansing, Mich.	1	......	5	......	5	8	7	......	......
	2	......	6	......	7	4	14	......	......
Madison, Wis.	1	7	9	18	13	4	10	......	......
	2	14	11	......	7	3	8	......	......
Ellendale, N. Dak.	1	13	3	......	9	......	8	[1] 6–7	14
	2	18	8	......	8	......	8	[1] 9–10	14
Fort Omaha, Nebr.	1	......	9	15	20	......	7	[2] 5	14
	2	......	......	......	12	......	12	[2] 1	......
Broken Arrow, Okla.	1	13	8	19	12	15	5	[1] 16–15	......
	2	20	11	15	5	......	10	[1] 2–5	......
Groesbeck, Tex.	1	8	8	13	8	......	10	5	7
	2	17	14	17	9	......	8	5	8
Fort Sill, Okla.	1	......	......	......	13	11	4	......	......
	2	......	......	......	11	......	11	......	......
Ellington Field, Tex.	1	......	10	......	12	......	......	......	5
	2	......	21	......	12	......	......	......	3
Kelly Field, Tex.	1	8	9	......	......	6	4	5	3
	2	8	17	......	......	......	6	9	2

[1] Kite observation.
[2] Kite observation at Drexel, Nebr., about 20 miles west of Fort Omaha.

These tests could be continued indefinitely, but it is believed that sufficient evidence has been brought forward to justify the conviction that these free-air maps are accurate. Are we not, therefore, justified in carrying on? If the answer is in the affirmative, we are obliged to give the maps the most thorough study possible in order to ascertain their value for day-to-day forecasting. Their value in relation to aviation is unquestioned, and, if the example of the Japanese meteorologists is to carry any weight with us, we can not escape the belief that these daily charts of free-air conditions will be useful in general forecasting.

THE MAPS.

The selection of dates for map drawing.—It is manifestly impossible to cover in a limited number of maps, the myriad interesting cases in which capricious nature checkmated the forecaster. Instead of selecting dates at random, however, it was believed that greater interest would attach to those in which the unexpected occurred. C. L. Mitchell, forecaster at the central office of the Weather Bureau, kindly selected a long list of dates of this character from which all the maps that follow, the first excepted, were drawn. These seem to offer much suggestive material. The original publication contains 22 charts, of which only 8 are given here.

The viewpoint.—The following groups of maps represent the culmination of effort in this paper. No attempt will be made to draw sweeping conclusions; there is no intention to force beyond the point of justification the significance of these charts. In other words, they must speak for themselves, and their value must be demonstrated by consistent day-to-day study and interpretation. It is desired only to present such running comment as seems pertinent and suggestive.

The charts.—For each date there are three maps; the first is a copy, so far as isobars and isotherms are concerned, of the weather maps except that the units have been converted. The black lines are sea-level pressure, the red, surface temperature, and the black shaded areas show regions in which precipitation occurred in the 24 hours *following the time of the map*. This last feature is not the same as that shaded area on the daily weather map, but corresponds to the shaded area on the map of the following day. This is for use in connection with the possible prognostic value of the free-air charts for precipitation. The two smaller maps show the pressure distribution, in black, at the respective levels. The red lines on these smaller maps are not isotherms in the usual sense, but are lines of equal value of θ or lines of equal temperature argument. In general, this conforms to the distribution of surface temperature and is somewhat representative of the distribution of free-air isotherms, but care should be taken not to interpret them as isotherms corresponding to the level of the isobars. They may be considered as approximate temperatures at some intermediate level.

CHART I.

December 17, 1919.—The especial features which rendered this date remarkable have been discussed by Mr. W. R. Gregg.[19] The highest velocity ever observed in the free air below 10 km. in the United States, 83 meters per second, was observed at an altitude of 7,200 meters on this date at Lansing, Mich. This observation was corroborated by numerous observations of extremely high velocities at the levels reached and a very rapid increase of speed with altitude at other stations, although no other observations reached so great an altitude. It was of interest, therefore, to draw the upper isobars for this date in order to see to what extent the computed isobars bore out the testimony of the observations. The result is striking.

Perhaps the first feature that will appear to the student is the complete obliteration of the sea-level pressure configuration below 1 kilometer. At 2 kilometers, the isobars are parallel over the eastern United States and the gradient steeper than at 1 kilometer. In other words, what appeared to be a "ridge" of high pressure at sea level has disappeared except for a suggestion of it in the bend of the isobars over Arkansas and Missouri at 1 kilometer. Even the southern development of the cyclone on the Atlantic coast is overrun at 1 kilometer by northwest winds.

[18] Meisinger, C. LeRoy: The weather factor in aeronautics. Mo. WEATHER REV., December, 1920, pp. 701–708.

[19] Note on high free-air wind velocities observed Dec. 16–17, 1919. Mo. WEATHER REV., December, 1919, pp. 853–854.

The reason for this sudden change within a small limit of altitude is not hard to find. It lies in the marked gradient of surface temperature which is accentuated and somewhat smoothed in the 1-kilometer distribution of θ. It is clear that the temperature distribution and not the surface pressure was the dominating influence on this day. The wind, in attempting to flow from above the warm region to the cold region was deflected by the earth's rotation with the result that it flowed nearly parallel to the isotherms.

The forecaster doubtless would have forecast westerly winds at a quite low elevation, but it is a question whether he would have anticipated that opposing winds at ordinary flying levels between New York and Chicago would have a force approximately equal to half the air speed of a commercial airplane. Or that a high-powered commercial dirigible flying the same route would have had its speed reduced to less than that of an express train. Or that the same craft flying from Chicago to New York would have been able to arrive at the destination several hours sooner than usual. These are facts of the greatest importance in the dispatching of mail and will be of greater importance as the activities of commercial aviation multiply. Free-air maps disclose the facts without surmise or guess.

CHARTS II–III.

March 14–15, 1919.—Preceding the first day of this period, a low pressure area had traveled along a curved path from the middle of the Oregon coast to the point in the northern part of Colorado, where it is seen on the sea-level map (Chart II). A well-marked high-pressure area is found over Ontario, and between the high and low centers lie evenly spaced isobars representing a difference of pressure of about 54 mb. The direction of movement of the low center is of chief interest in this series. Judging from the forecasts of colder in the west portions of Nebraska and South Dakota for the following day, it was apparently anticipated that the cyclone would move more to the east than it actually did. In fact, as the map for the 15th shows, the north component of motion exceeded that of the east component and the center appeared in north central North Dakota (Chart III). The map for the following day does not extend far enough north for one to ascertain the location of the lowest pressure, but it is not unlikely that it lies in a general line with the direction of the previous day. This motion was from a little south of southwest. The sea-level isobars the first day had a trend from southeast to northwest over the eastern United States, the second day more from the south, the third day from the southwest. What do we find aloft?

On the first day, instead of high pressure so far to the north as pictured at sea level, it appears more as a general high pressure region east of the United States producing winds at 1 kilometer below latitude 40° from the south-southwest and north of that latitude from the southeast. At 2 kilometers, the isobars are from the southwest. With general high pressure to the east and a well-defined isobaric trend from south-southwest to north-northeast at 2 kilometers, it is quite apparent that the movement of the cyclonic center is definitely related. The 15th shows this southwest current still better established and, judging from the closer isobars, of higher velocity. The direction of movement of this center throughout the period is parallel to these isobars. The developing "wall" of high pressure in the free air extends parallel to the Atlantic coast—a fact not discernible on the sea-level map. The progressive northward bulging of the θ-isotherms shows the effect of the importation of warm, southerly air.

It is apparent here, as it will be in later maps, that sea-level anticyclones, at least in winter, are not reproduced in the free air with the positiveness characteristic of cyclones. The Colorado cyclone, for instance, is apparent at each level, but the eastern high pressure does not conform to that at sea level, and the small high-pressure region in Nebraska and South Dakota on the 16th does not even appear on the 1-kilometer map, being overrun by westerly or northwesterly winds.

CHARTS IV–V.

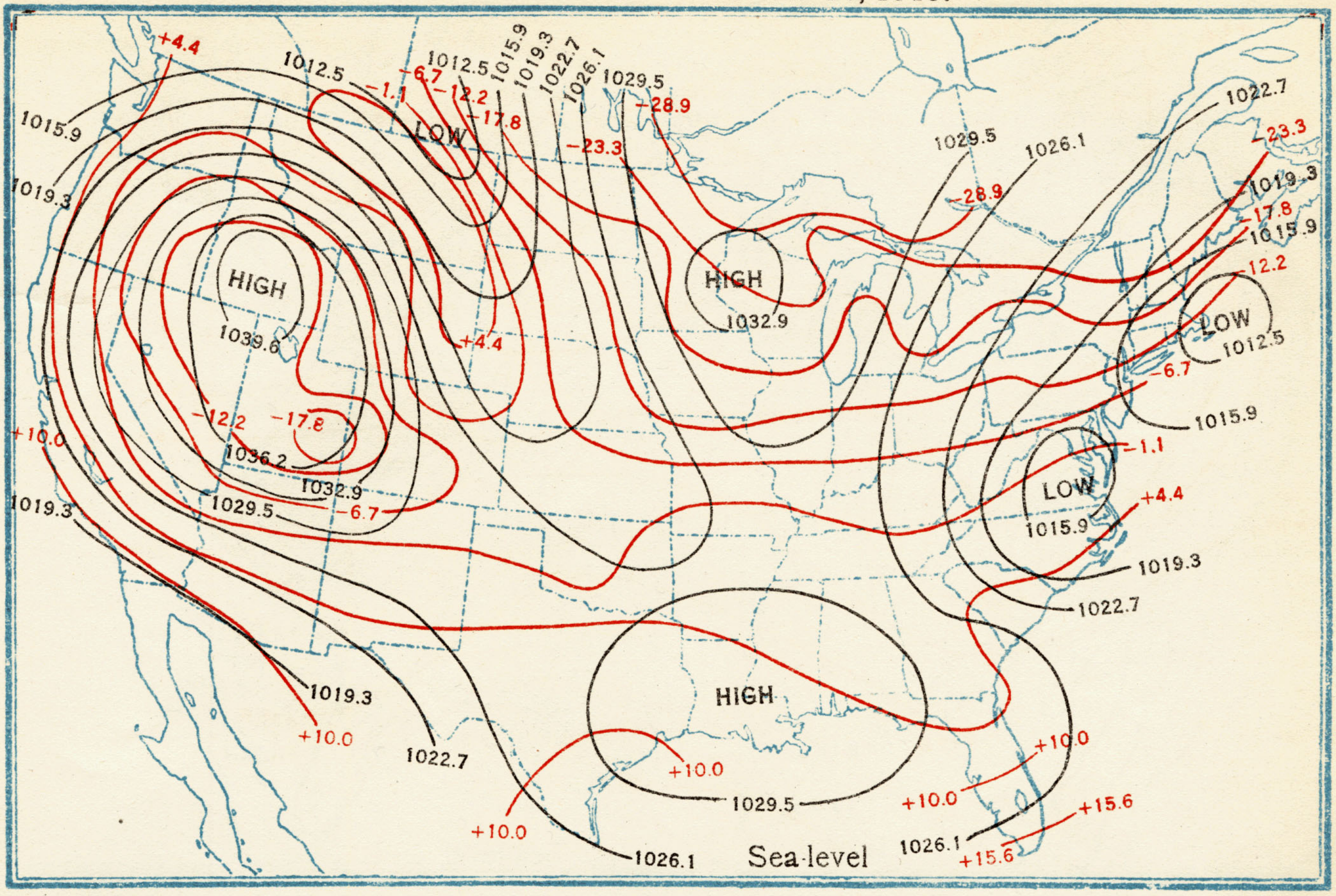
October 16–17, 1914.—In the original publication, this series of maps extends from October 11 to 18, 1914, but only two of these have been selected for reproduction here. Preceding the first of these two maps, on the 13th, there appeared on the sea-level map what might be described as a tongue of low pressure overspreading the country from the Gulf of Mexico. On that date this does not appear in the free-air maps. The only response to low-pressure activity in the Gulf region comes on the 15th, when the low center at 2 kilometers is found over southern Alabama, while another center of equal intensity is over Lake Superior. The following day there has occurred what appears as a merger of the two with a very much intensified center in west-central Illinois.

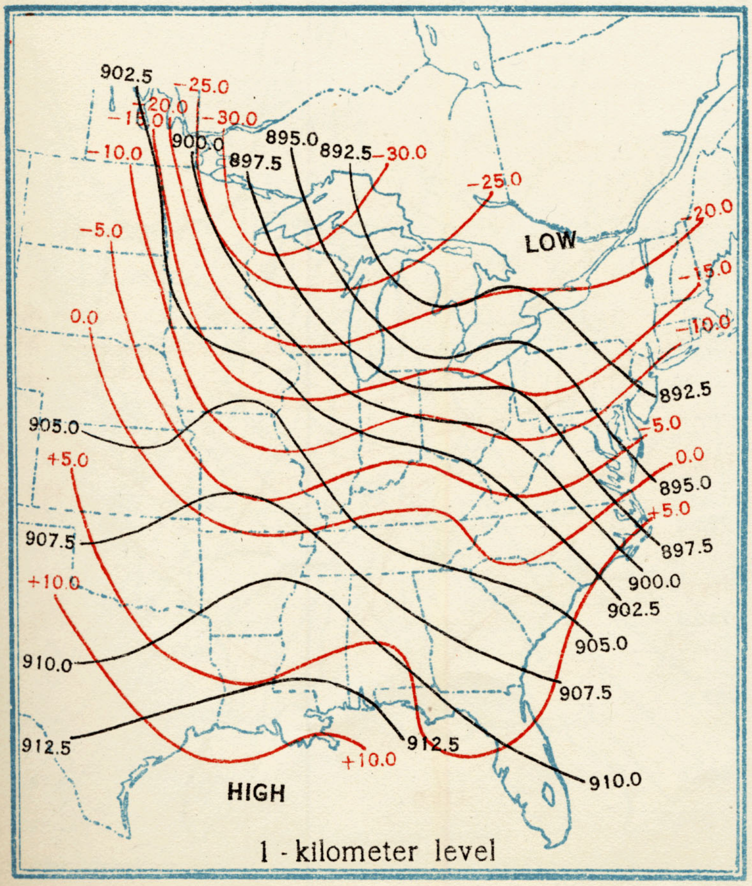
This disturbance is nearly circular, its importational power is most perfectly developed, and low temperature is found intruding from the west until the temperature of the south half of the formation is lower than that of the north half. This is significant with respect to rainfall. Here is cold dry air imported from the west and northwest; the warmer, moisture-laden air from the Gulf and South Atlantic coasts is drawn with pinwheel symmetry into the north half of the storm. This effect, apparent at both levels in the free air, but complicated at sea level by the tri-centered low area in the east, seems to explain the occurrence of precipitation in the north half of the storm and but little south of the free-air center.

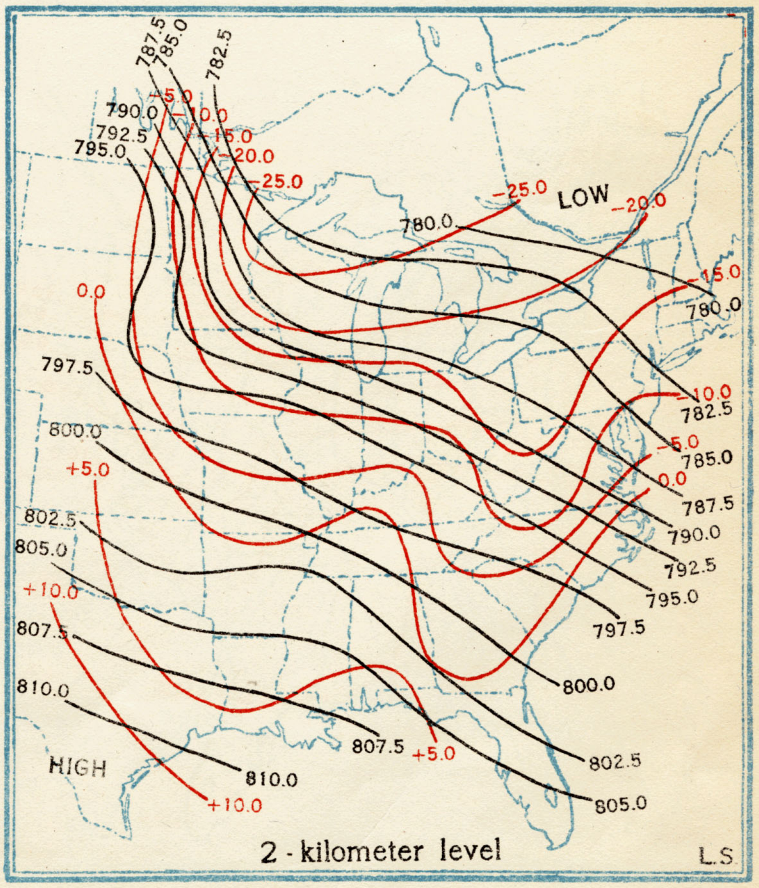
The shifting of the center to the west in the free air is also the result of the marked development of the temperature contrast between front and rear of the cyclone.

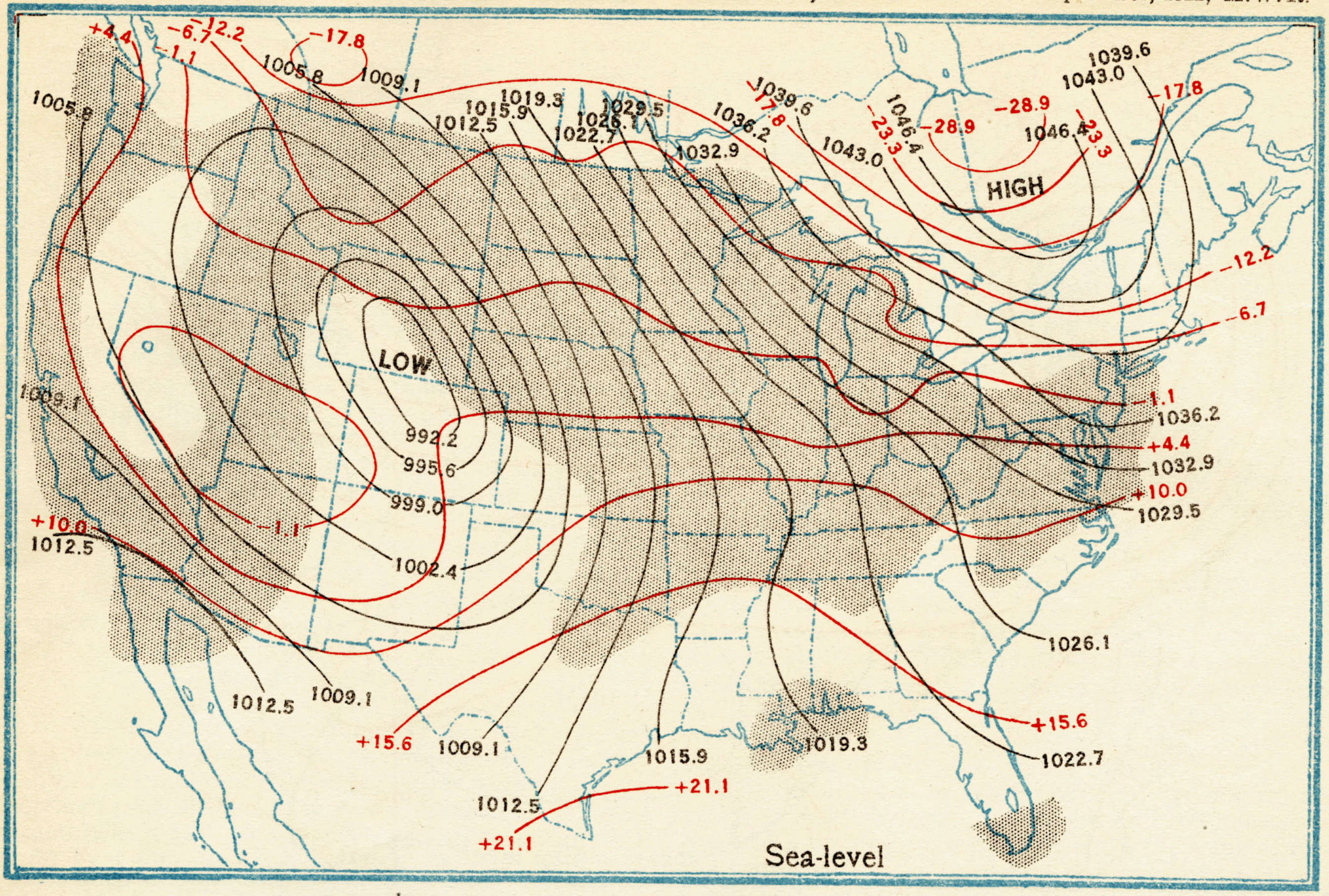
Having actually curled about itself streams of air of considerable temperature difference, it is found that on the 17th there is an isolated mass of cold air cast adrift in the southeast quadrant (1 kilometer) and a symmetrically located mass of warm air detached north of the previous storm center (2 kilometers). This latter warm air was certainly influential in splitting the low pressure in two at the 2-kilometer level. In general, this might lead to the suggestion that the anomalous temperature distribution is the cause of the rapid disintegration of what seemed on the 16th to be a well-developed circular cyclone in the free air. In other words, it is conceivable that the storm literally destroyed itself, at least in the lower layers, through its own vigor in mixing air currents of markedly differing temperature and humidity.[20] On the succeeding dates, the barometric situation changed rapidly, and a new régime was begun which would introduce a whole new series of charts.

[20] Since sending the manuscript to press, a new paper by J. Bjerknes and H. Solberg entitled, "Life cycle of cyclones and the polar front theory of atmospheric circulation" *Geofysiske Publikationer*, Vol. III, No. 1, Kristiania, 1922) has appeared. In this paper it is shown how through the process of "occlusion," masses of warm air are cut off from the source and the dissolution of the cyclone follows.

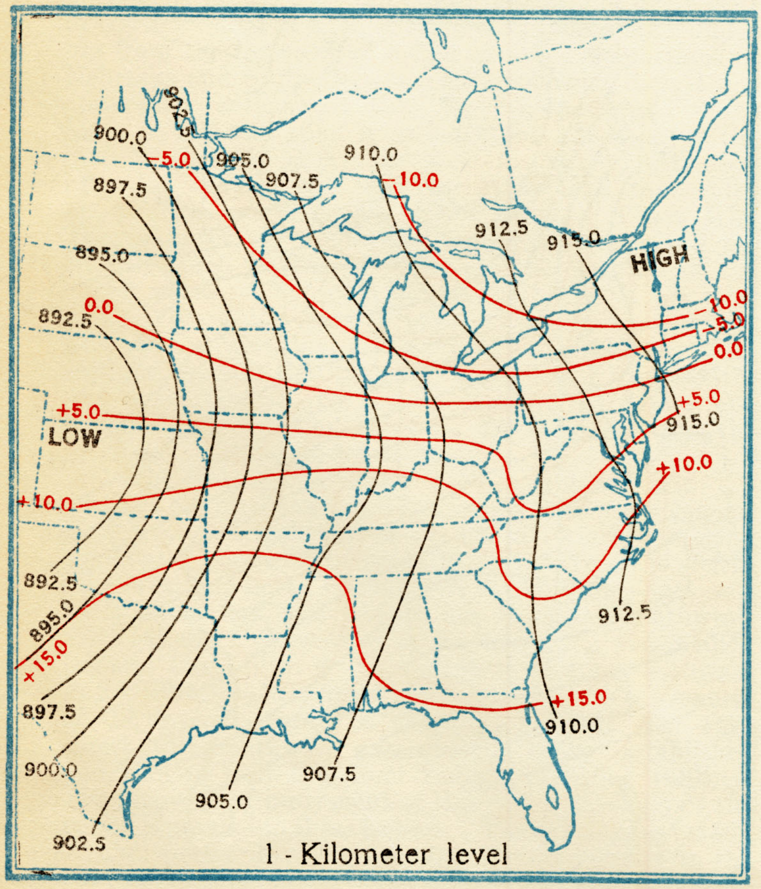

HIGH
1039.6
HIGH
1032.9
HIGH
LOW
LOW
LOW
Sea-level


LOW
HIGH
1 - kilometer level

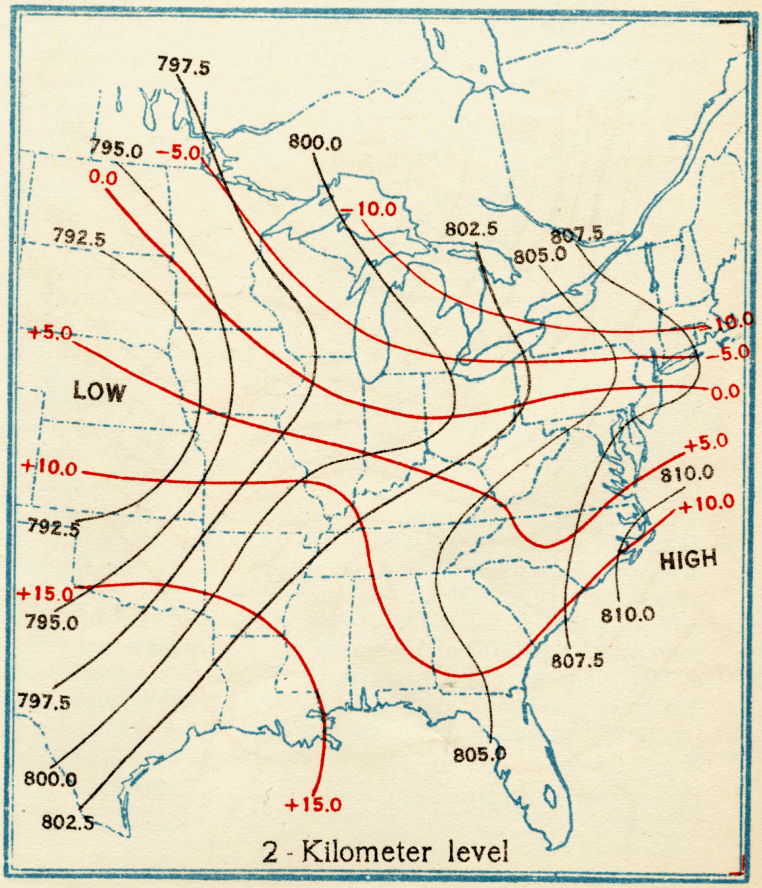

LOW
HIGH
2 - kilometer level
L.S.



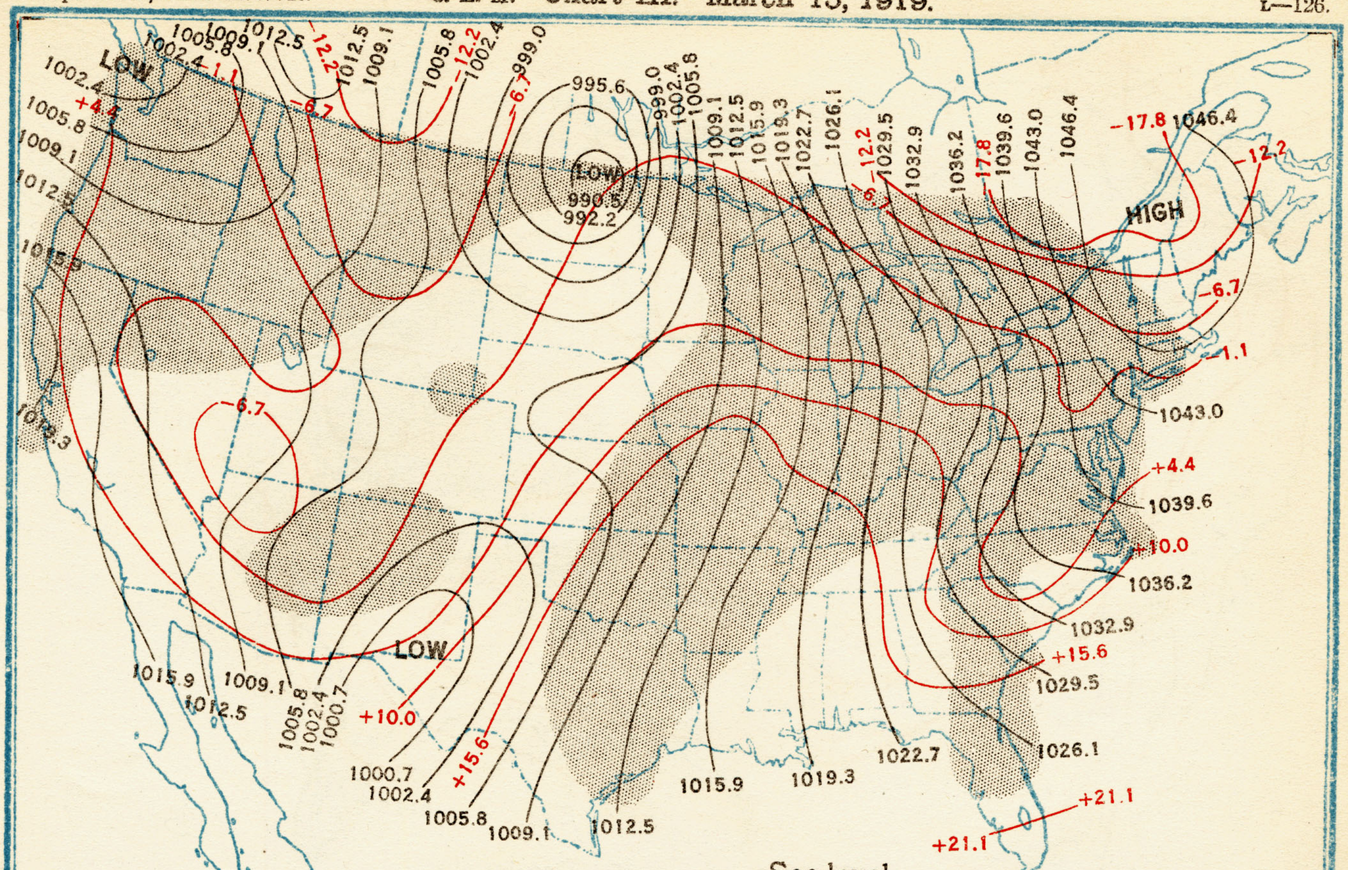
Sea-level



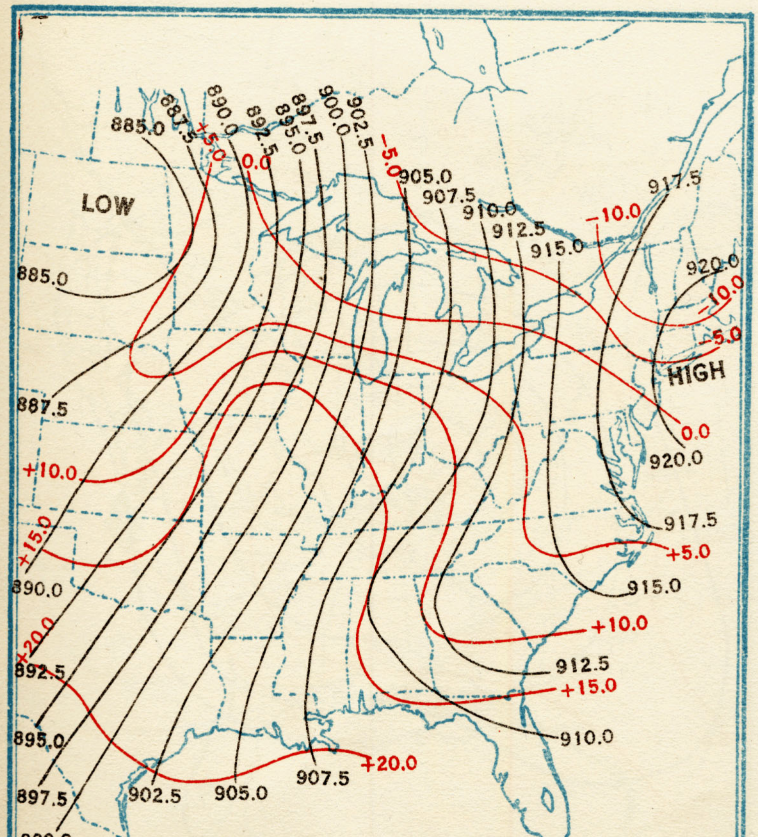
1-Kilometer level



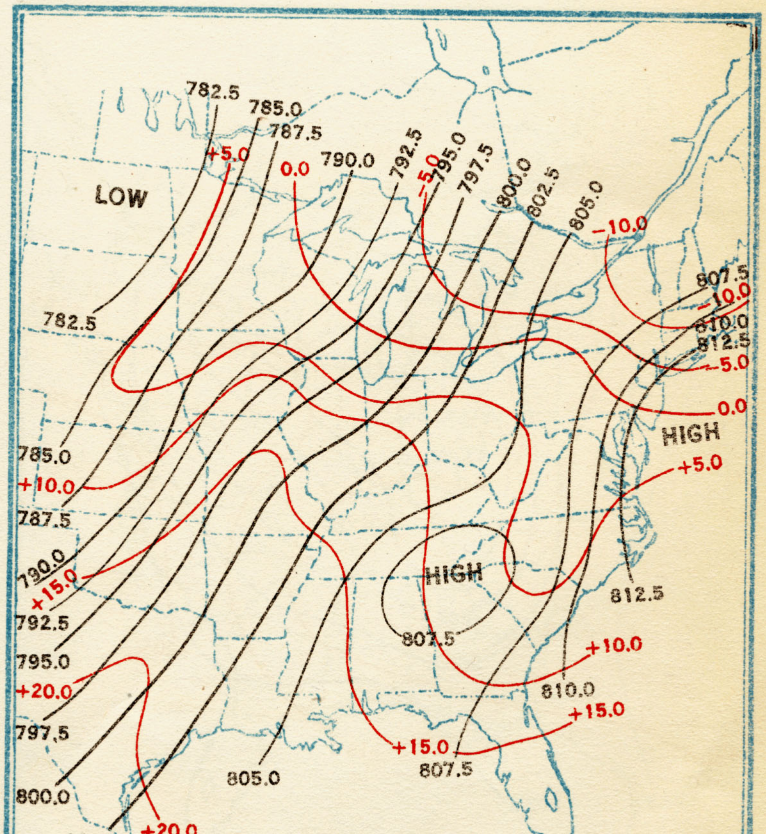
2-Kilometer level



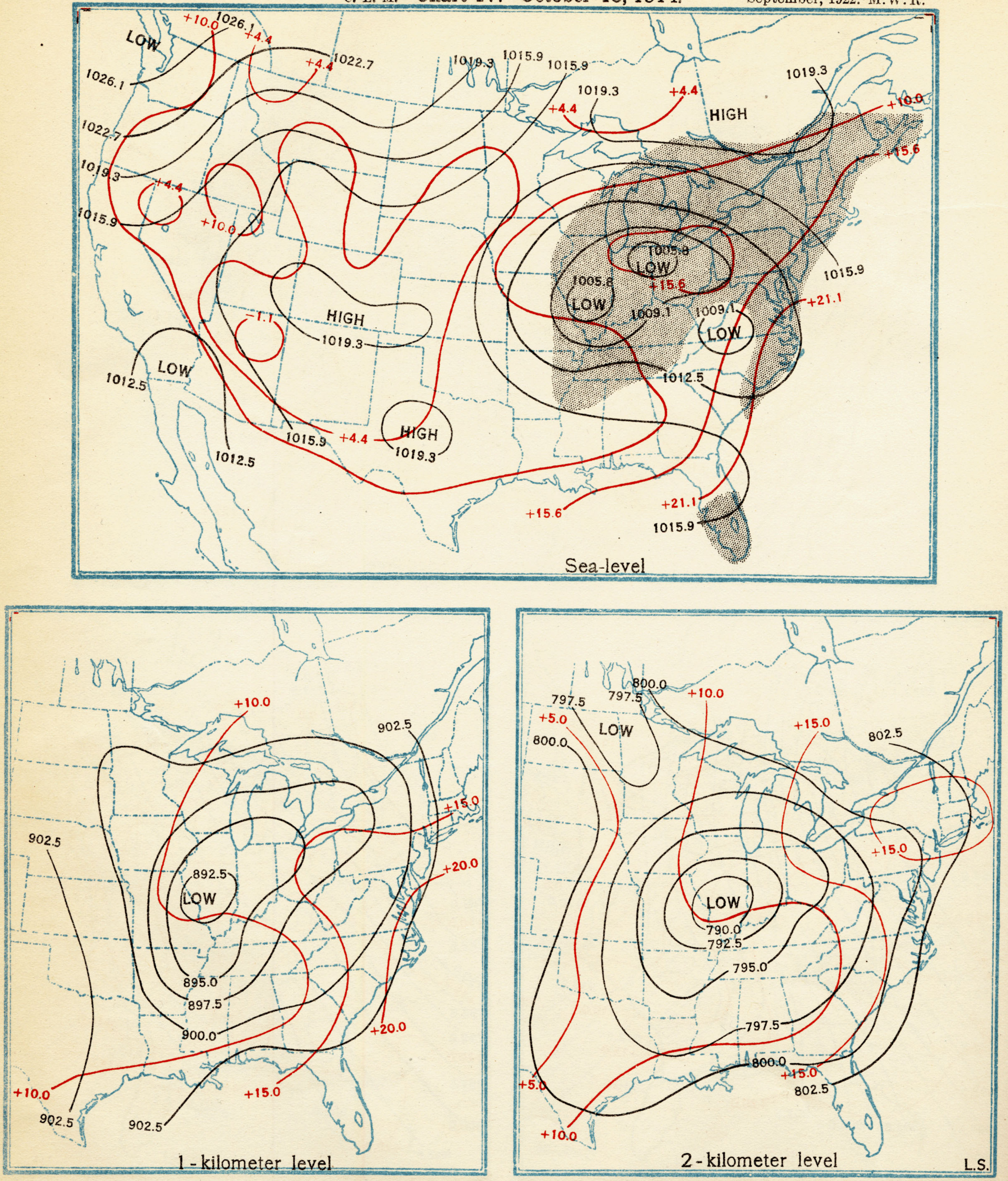
Sea-level

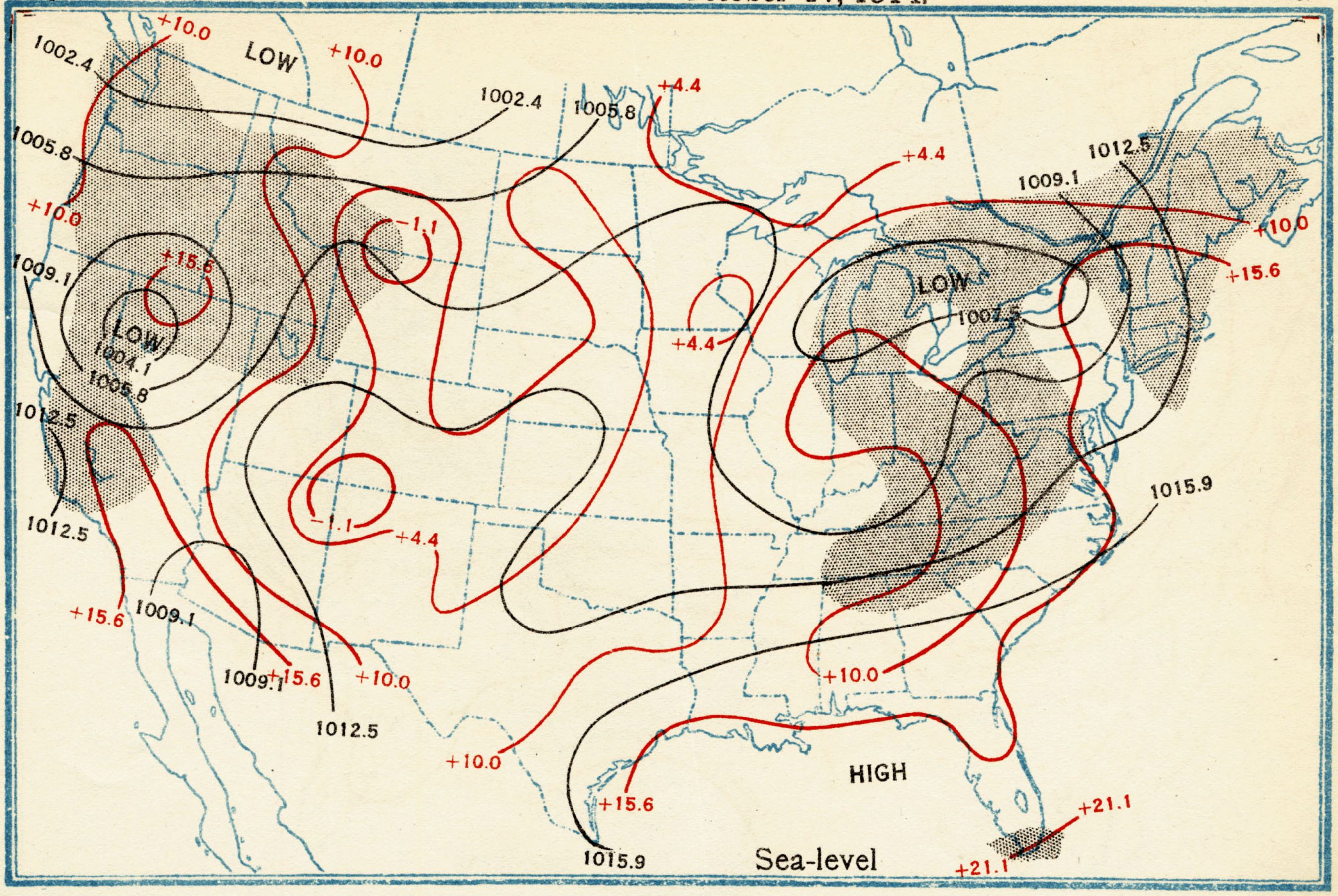


1 - Kilometer level

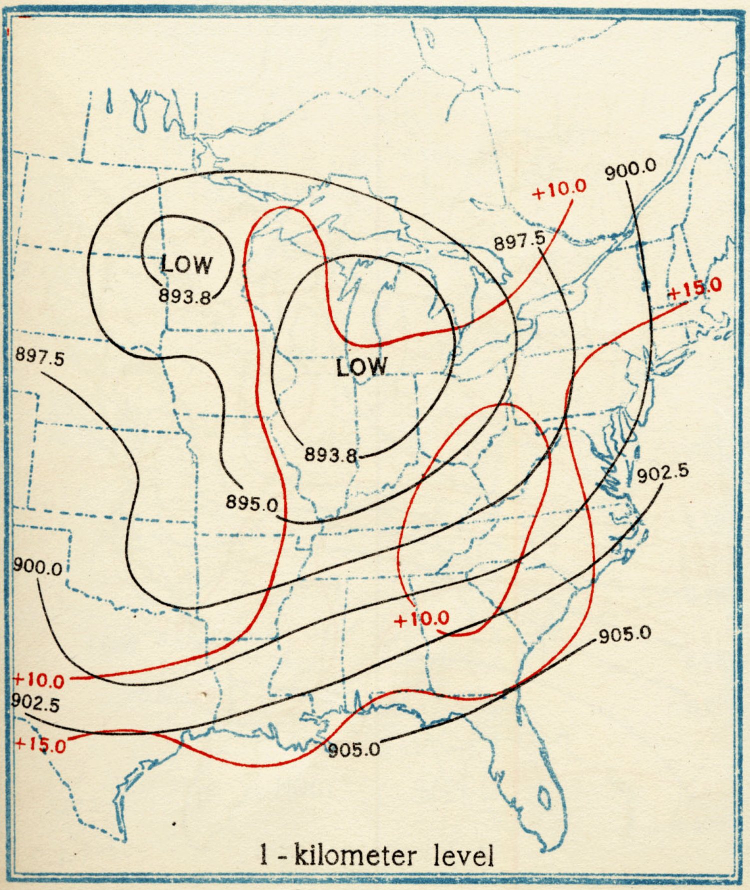


2 - Kilometer level

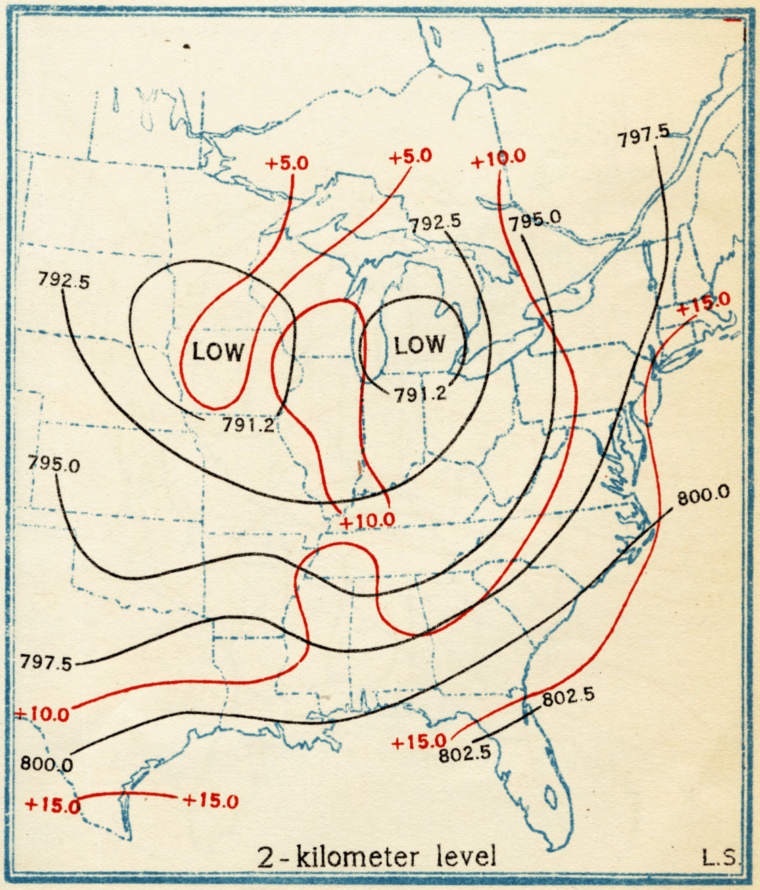

LOW
HIGH
1026.1
1022.7
1019.3
1015.9
1012.5
1009.1
1005.8
+10.0
+4.4
+15.6
+21.1
-1.1
Sea-level
892.5
895.0
897.5
900.0
902.5
+10.0
+15.0
+20.0
1-kilometer level
790.0
792.5
795.0
797.5
800.0
802.5
+5.0
+10.0
+15.0
2-kilometer level
L.S.



Sea-level



1-kilometer level



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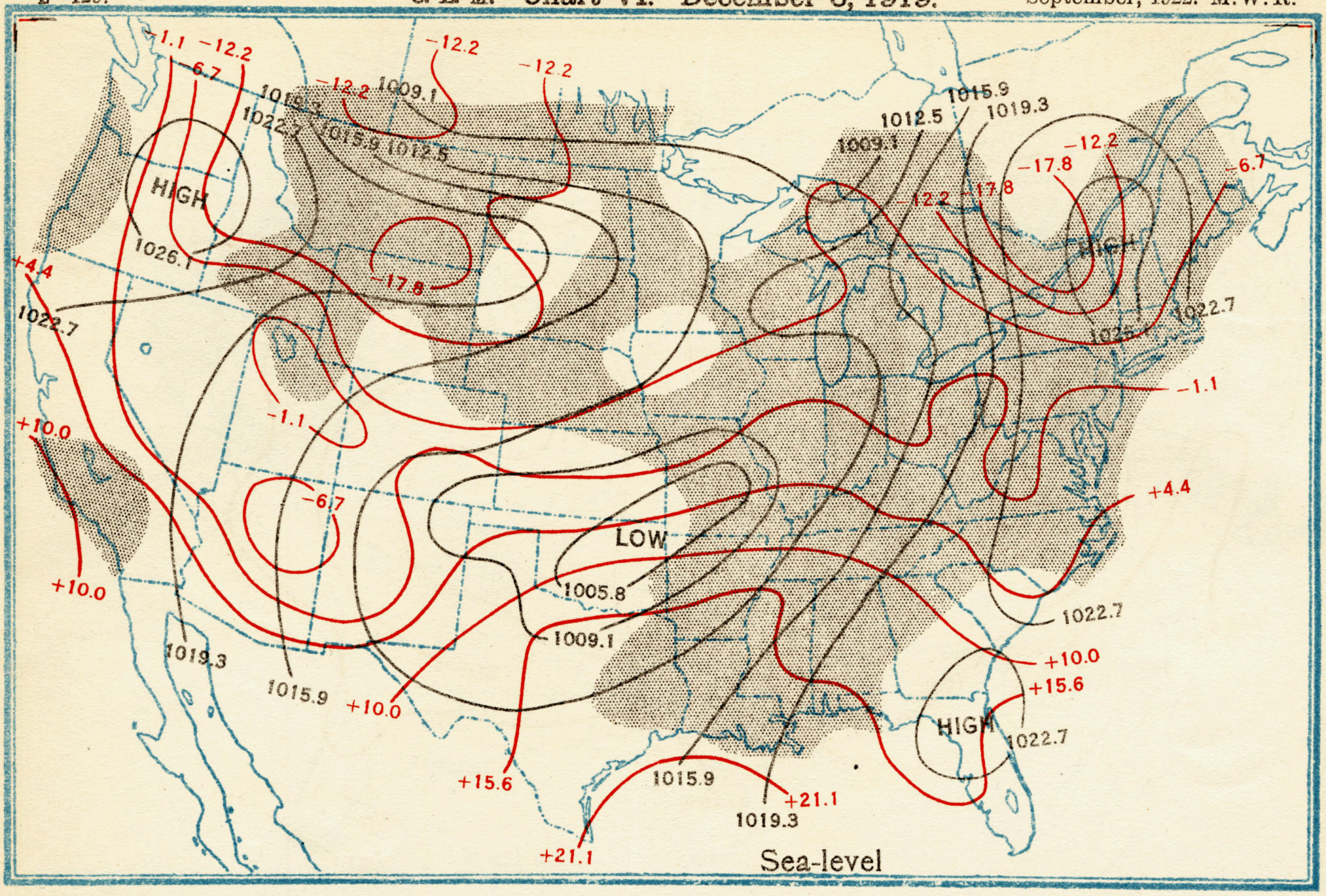
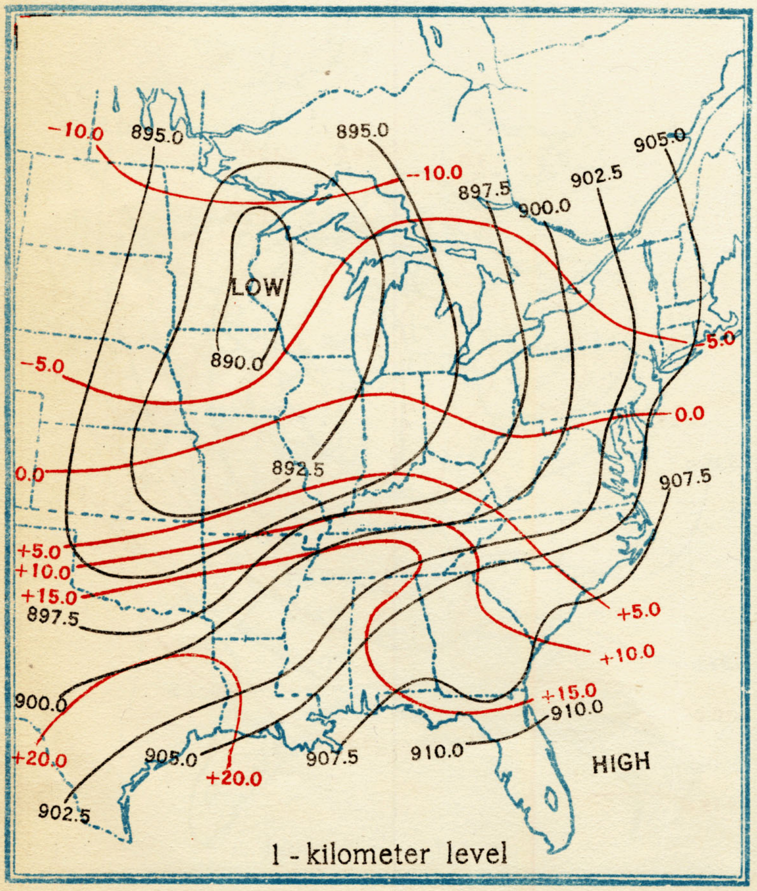


Sea-level



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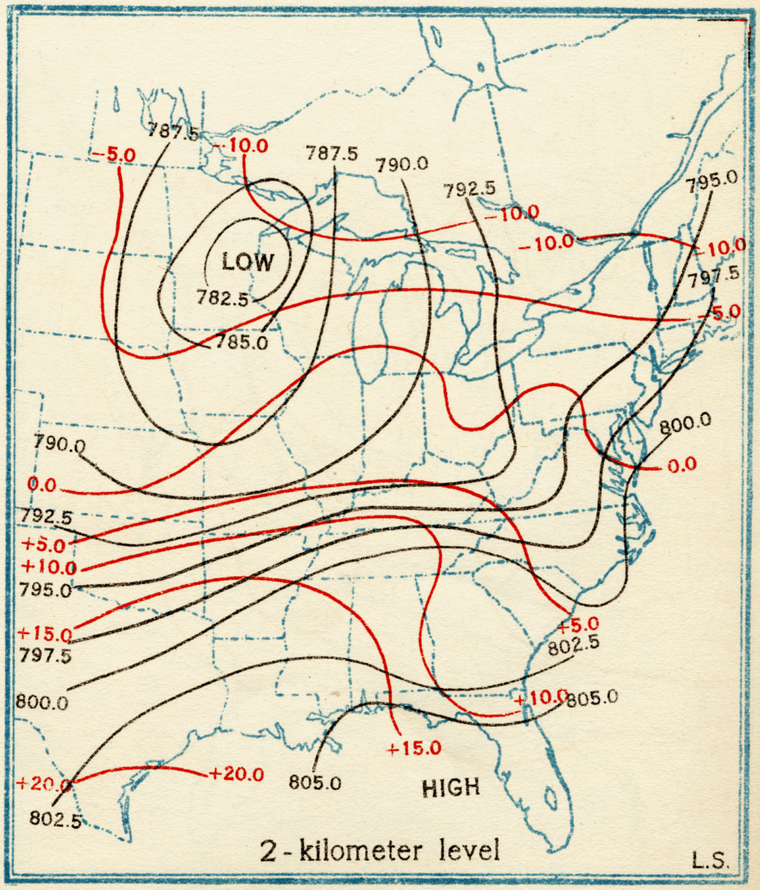

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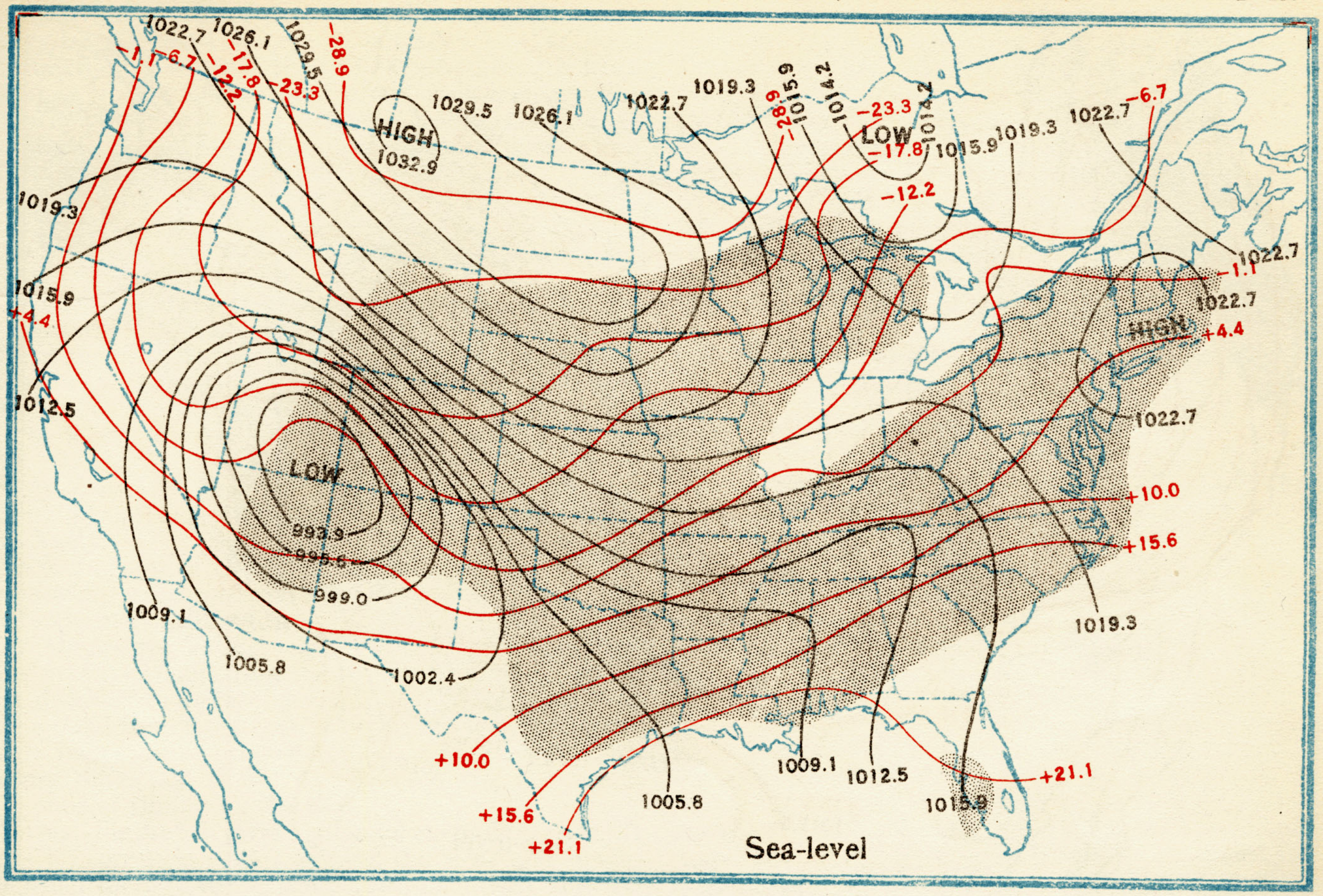
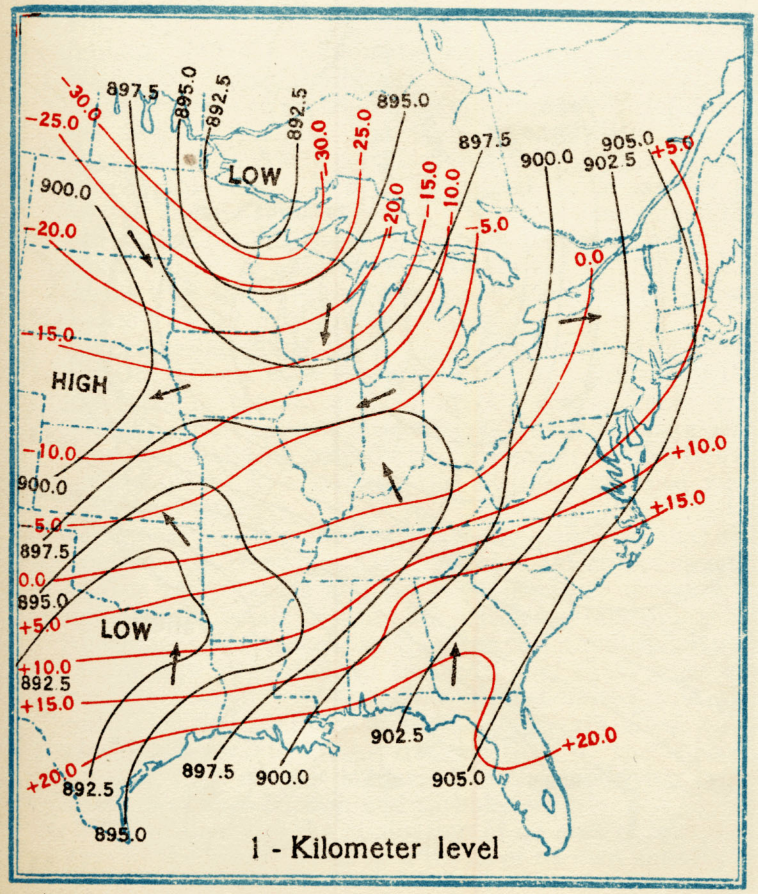
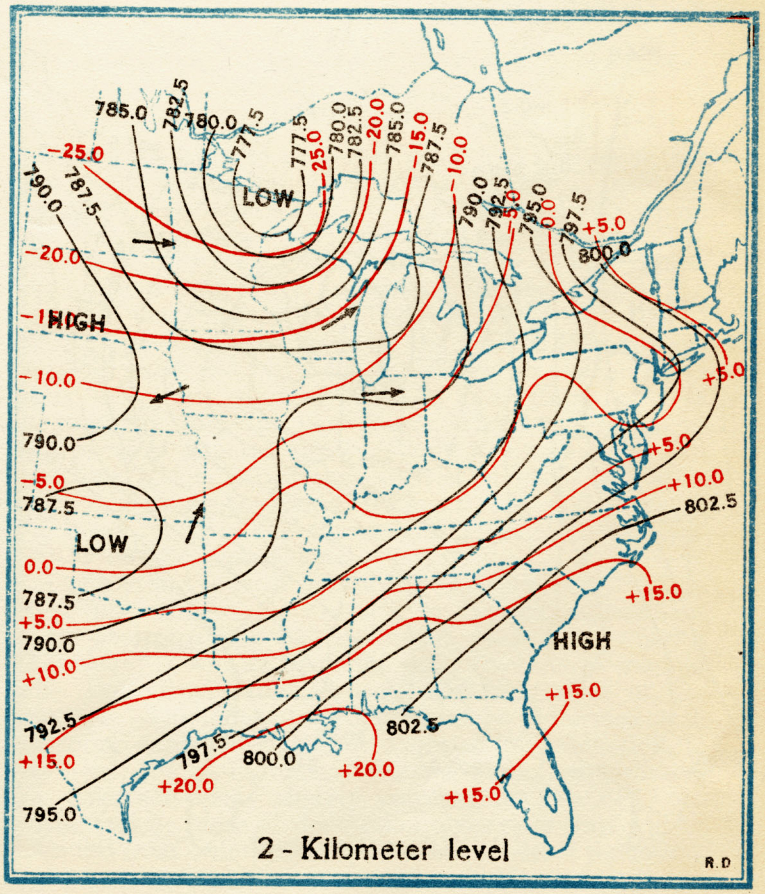


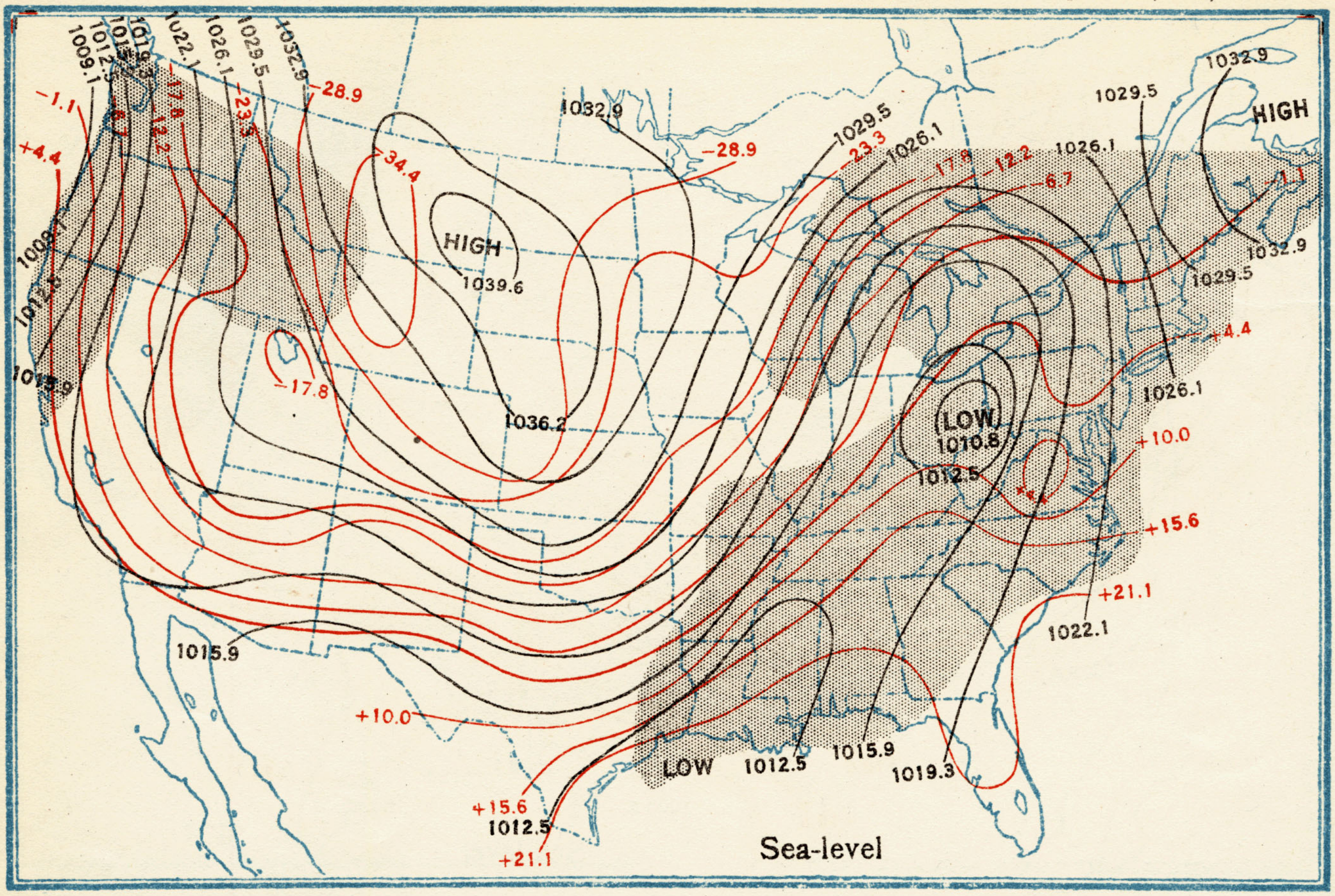
Sea-level



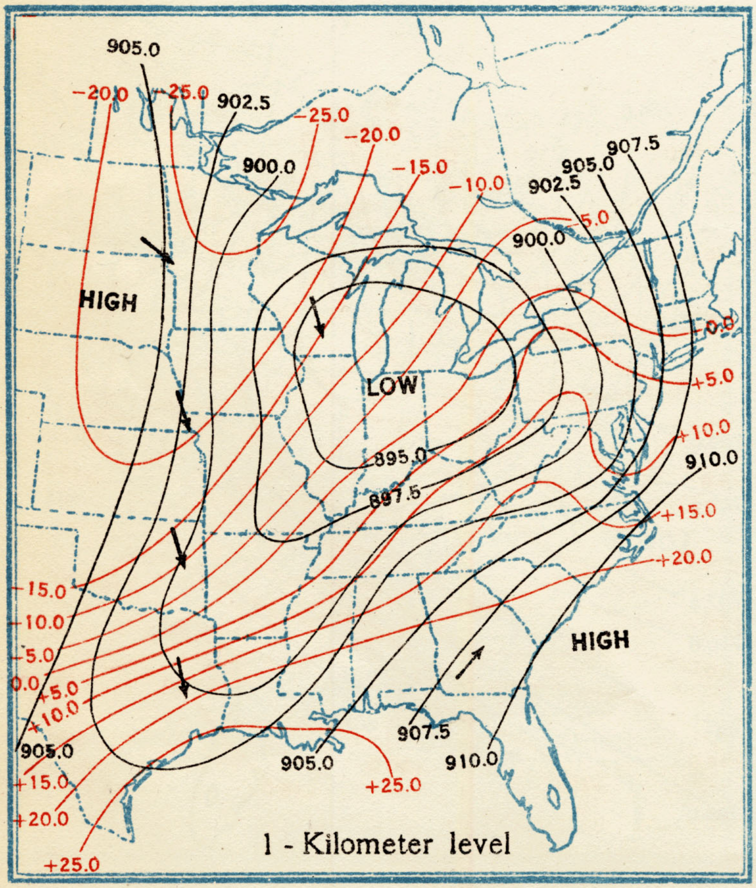
1 - Kilometer level



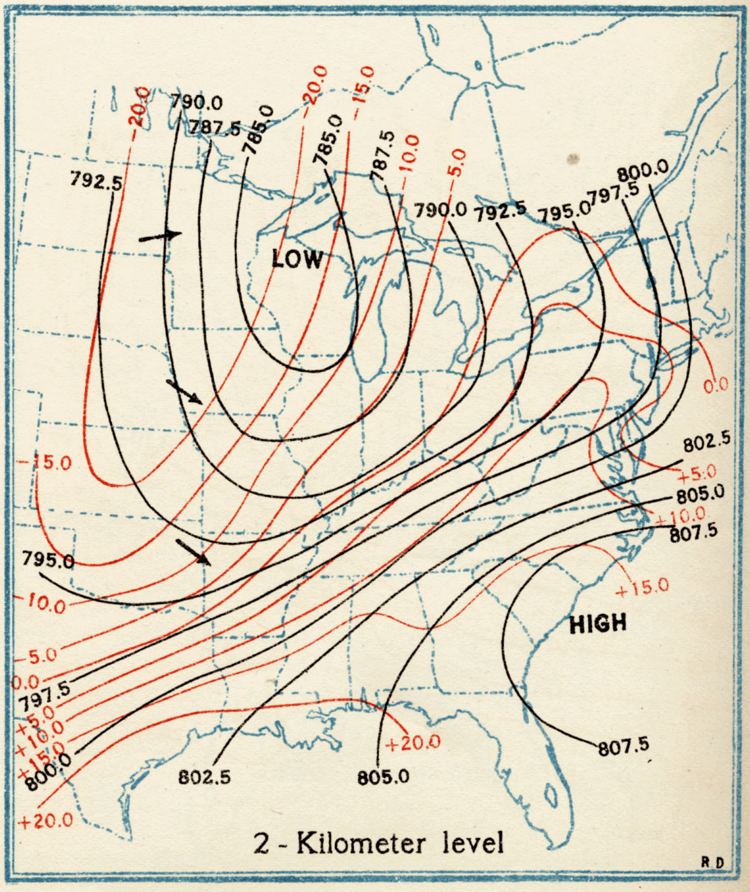
2 - Kilometer level



Sea-level



1 - Kilometer level



2 - Kilometer level

Attention is again invited to the importance of these maps in aviation. Here we have had a wide expanse of country largely cloud covered. Had aerological stations been functioning in 1914, they could have afforded little assistance in the matter of free-air movements. The circulation aloft was well defined, but it was not so apparent at the surface; the gradients aloft were quite steep and it is likely that high winds prevailed. Would these maps have aided the aviator?

CHARTS VI–VIII.

December 6, 8, and 9, 1919.—On the 5th and the following days the low-pressure center in the free air was north of the sea-level center; in fact, when the sea-level cyclone was centered in eastern Oklahoma the upper center was in Minnesota. Such shifting was undoubtedly the result of the low temperatures prevailing in the north. With the establishment of a strong southwesterly drift, the temperature contrast was accentuated so that the isobars followed the trend of the isotherms very closely.

The low center in the Lake region, being circular and slow moving, developed considerable intensity and introduced extremely cold air, farther and farther to the south in the Mississippi Valley, while the front was being fed with a steady stream from the southwest. The meeting place of these two drifts of differing temperature occurred along a band from northeast Texas to Indiana, where the surface temperature gradient gave a simultaneous temperature difference of 20° C., between the north and south ends of Illinois on the 9th.

The map for the 9th gives a splendid example of the shift of the low-pressure center toward the west and northwest when there is strong temperature contrast between front and rear. In this case the sea-level center is in West Virginia, the 1-kilometer center is in northern Indiana, and the 2-kilometer center is in west central Wisconsin. How significant, then, must be the effects of importation of air from different sources—air of different moisture content and temperature—about depressions having the same core, but with this core sloping at a considerable angle from the vertical. The regions of rainfall in this series, especially in those maps near the end of the period, show this significance strikingly. It is interesting to observe how closely the rainfall region agrees with the sweeping streams of southerly air drawn forward by the pressure disturbance.

For the benefit of those who are desirous of observations to substantiate the rather startling shifting of the low-pressure center revealed in this series, Table 4 is offered. Pilot-balloon observations were limited in altitude practically universally to 1 kilometer or less, but at several of the kite stations the altitudes attained were somewhat greater.

Summary.—This cursory study has indicated that the fundamental considerations regarding the interaction of surface temperature and sea-level (surface) pressure in influencing free-air pressure are justified. Meteorological phenomena, influenced, as they are, by a multiplicity of factors, are often difficult to study, and these maps are not exceptional. Nevertheless, it is believed that the results of the interplay of these factors are much more clearly discernible in the free air than at the surface, because they are not subjected to the modifying influences of surface friction and turbulence.

The evidence of the dissipation of an area of low pressure in the lowest levels as a result of its own activity in importing air of strongly contrasting temperature, seems highly suggestive. The displacing of free-air centers through strong temperature contrasts, the conduct of free-air secondaries and their influence on surface conditions, the relation of these effects to the distribution of precipitation, are all subjects rich in importance to general forecasting.

The importance to aviation interests has already been emphasized. The perusal of these charts shows clearly that a correct surmise of what the winds are doing aloft is often impossible from the sea-level chart. This knowledge is, however, absolutely essential to the safe and efficient conduct of aerial traffic.

TABLE 4.—*Free-air winds at aerological stations December 8–9, 1922.*

[Speed in meters per second.]

I. OBSERVATIONS WITH KITES.

Station.		Dec. 8.		Dec. 9.	
		1 km.	2 km.	1 km.	2 km.
Royal Center, Ind	Direction	ENE.	[1] W.		
	Velocity		8.9		
Ellendale, N. Dak	Direction	NW.	W.	WNW.	WSW.
	Velocity	10.7	12.3	7.9	7.4
Drexel, Nebr	Direction	ENE.	[2] ENE.	NNW.	WNW.
	Velocity	12.7	2.4	13.4	12.3
Broken Arrow, Okla	Direction	SE.	SSW.	NNW.	[3] WNW.
	Velocity	12.5	16.7	16.2	17.6
Groesbeck, Tex	Direction	S.		[4] NNW.	
	Velocity	7.2		17.3	

II. OBSERVATIONS WITH PILOT BALLOONS.

Ithaca, N. Y	Direction	W.			
	Velocity	2			
Lansing, Mich	Direction	NNE.			
	Velocity	1			
West Point, Ky	Direction	SSE.			
	Velocity	13			
Madison, Wis	Direction	N.	SW.	NNW.	
	Velocity	3	12	10	

[1] 1 p. m. observtion. [2] 1,815 meters. [3] 1,842 meters. [4] 658 meters.

CONCLUSION.

This study aims to carry the process of free-air reduction to the point where it can be performed at meteorological stations with a facility equal to that with which sea-level reductions are performed at present. The process is fully explained, the accuracy of the resulting maps is supported by much evidence, and a few specimen maps are drawn. The real test of the value of these maps can not be made by the author; that demonstration must rest with the forecaster, experienced, as he is, with daily weather controls, and sympathetic, as he must be, with the new charts, which will reveal to him pictures hitherto apparent only as fragmentary impressions. It is hoped that such a trial will lead to a more adequate conception of the processes at work in the lower levels of the atmosphere and a deeper appreciation of three-dimensional weather.

The method is both practicable and practical. There is no unsurmountable obstacle to the accomplishment of its objects and it can be turned at once into useful channels. It will assist in the most economical manner with the visualization of the third dimension of the weather. The labor of reduction can be performed with no more experience than is required for reduction to sea level, the basic material for the reduction embraces no observation not already required for the daily reports, and no more of the station observer's time will be required than is devoted at present to sea-level reduction.

The maps would give additional knowledge of the free-air winds. From the examples given in this paper it is obvious that many cases occur when the free-air conditions can not be accurately judged from sea-level data. These often occur at times of stormy weather when pilot-balloon observations are not available. Such times are likewise trying to the aviator, and it is then that he wants the most reliable advice.

It is believed that these maps will eventually have significance for general forecasting because of the close relation between free-air conditions and certain phases of surface weather, precipitation, cloudiness, and temperature. If these maps are found useful in the eastern United States and those tentative plans which have been suggested above for attacking the pleateau are found fruitful, there is the encouraging possibility that we may realize an ambition to blanket our country from coast to coast with a weather map of three dimensions. This may not be a universal panacea for all forecasting ills, but it will at least afford a glimpse of the physical processes at work, and lift us from the annoying disappointments of empiricism a little nearer to that ultimate goal toward which all students of weather forecasting are striving.

J. BJERKNES AND H. SOLBERG ON THE LIFE CYCLE OF CYCLONES AND THE POLAR FRONT THEORY OF ATMOSPHERIC CIRCULATION.[1]

By ALFRED J. HENRY.

[Weather Bureau, Washington, D. C., November 3, 1922.]

These two young Norwegian meteorologists have our best thanks for the clear presentation of their views on that perpetually interesting question of the origin and maintenance of cyclones and anticyclones. Readers of the REVIEW have had some intimation of the research work in forecasting that is being conducted at the Bergen Geophysical Institute from Miss Beck's paper in the August issue.[2] That article will serve as a prelude to the more formal presentation of the subject in the paper under review.

The elder Bjerknes, from a study of weather charts on which lines of flow were depicted and from other considerations, was led to a theory of the formation of cyclones and anticyclones, the germs of which, according to his own statement, are to be found in the writings of Dove and Helmholz. The latter in a paper on Atmospheric Motions[3] has shown that there is always a tendency toward the formation of a surface of discontinuity between air strata of different density which lie contiguous one above the other, and that at the bounding surfaces of such strata the conditions are ripe for the formation of atmospheric waves as soon as a lighter stratum lies above a denser one.

Professor Bjerknes has developed these ideas and applied them to the explanation of the origin and maintenance of cyclones and anticyclones. The air strata of different density most frequently met in nature are the two great currents, one flowing toward the Pole, the other toward the Equator. In a sense these are the counter currents of Bigelow and the opposing currents of Dove. How these currents act and react to form cyclones and anticyclones is perhaps best visualized from a drawing which the authors present under the title "Idealized cyclone." This diagram appeared in the August REVIEW, on page 404. They describe the principal features of the cyclone as consisting of two essentially different air masses, the one of cold, the other of warm origin. The two air masses are separated by a fairly distinct boundary surface which runs through the cyclone and which the authors believe may continue more or less distinctly through the greater part of the troposphere, being everywhere inclined toward the cold side at a small angle with the horizontal, say 1° or even 0.1°.

In the Northern Hemisphere the warm air is conveyed by a southwesterly or a westerly current on the southern side of the depression.[4]

At the front of this current the warm air ascends the wedge of colder air and gives rise to precipitation (warm front rain).[5]

The warm current is simultaneously attacked on its flank by cold air masses from the rear of the cyclone. Thereby part of the warm air is lifted and precipitation is formed (cold front rain).[6]

THE LIFE CYCLE OF CYCLONES.

The authors say that the more recent investigations have shown that the type of cyclone above described represents a certain stage of development in the life of a cyclone. The successive changes in form and structure are schematically shown in Figure 1, in which type *c* or *d* corresponds to the "ideal" cyclone mentioned above.

In the earlier stages the same cyclone has the structure shown in *a* and *b* and it will successively pass through the forms *e*, *f*, *g*, and *h* of Figure 1. As may be seen by that figure, the initial stage of formation is pictured in *a* wherein two oppositely directed currents a cold easterly (from the east) adjacent to and on the same level with a warm westerly (from the west) is separated by a nearly straight boundary.

At the place where the new cyclone is to be formed this originally straight boundary bulges out toward the cold side as in *b*, and the center of the cyclone will be found at the top of the projecting tongue of warm air. The tongue of warm air is identical with the warm sector of the cyclone, and the ascending air from this warm tongue forms the "warm front" rain and the "cold front" rain shown in *c* and *d*, respectively. This newly formed cyclone follows the current of warm air eastward and is propagated as a wave on the boundary surface between warm and cold air.

During the eastward motion, the amplitude of the warm wave increases (in a horizontal N-S direction as in

[1] *Geofisiske Publikationer*, Vol. III, No. 1: Kristiania, 1922.

[2] Pages 393-400.

[3] The mechanics of the earth's atmosphere. A collection of translations by C. Abbe, *Smithsonian Collections No. 843.*

[4] For the eastern part of the United States I should say that this specification should be modified to read the warm current is conveyed by a southwesterly to a southeasterly current on the southern or eastern side of the depression.—EDITOR.

[5] This is, of course, a very generalized statement to which there are many exceptions, so far as precipitation is concerned. In the case of a shift of the wind from offshore to onshore, when the land surface is quite cold precipitation occurs regardless of the position of the cyclone center, particularly along the Middle Atlantic coast.—EDITOR.

[6] In the United States cold front precipitation is not strongly marked in winter except as snow flurries in mountain districts and on the lee shores of the Great Lakes; in summer, however, the precipitation of a cyclone may be confined to cold front rain, which in many cases is clearly associated with the "wind shift" line in the rear.—EDITOR.